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THE ROLE OF HUMAN ERROR IN DESIGN, CONSTRUCTION, AND RELIABILITY OF MARINE STRUCTURES

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THE ROLE OF HUMAN ERROR IN DESIGN, CONSTRUCTION, AND RELIABILITY OF MARINE STRUCTURES

This report presents a state-of-the-art assessment of the influences of human error on the design, construction, and reliability of marine structures. The objective of this study was to establish guidelines to consider the effects of human errors in design and construction of marine structures and the formulation of design criteria.

This study is part of a five-year SSC research program to apply reliability technology and develop probability based design criteria for ship structures. Thus far, this program has addressed a variety of sources of uncertainty and ship design considerations that influence probability based design guidelines for ships. Human and Organization Errors (HOE) have not been explicitly addressed even though HOE is the major contributor to lack of structural reliability.

This study has categorized human factors, considered relevant case studies, identified qualitative and quantitative processes for evaluating the incidence and effects of human error, studied the impacts of human error on design guidelines, and evaluated how marine critical structural components and systems should be designed to accommodate HOE.

This study recommends two fundamental approaches to improve the management of HOE in design and construction: 1) improve the management of the causes to reduce the incidence of HOE, and 2) improve the management of the consequences to reduce the effects of HOE. Responsibilities for such improvements are suggested. HOE prevention techniques stressed include personnel selection, training, process auditing, testing (destructive and non-destructive), and external verification. HOE mitigation techniques stressed include design of robust, damage tolerant structural systems, and verification and audit of the portions of the design process that have the most important influences on structural reliability.

J. C. Card
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

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16. Abstract

This project addressed the following key questions. What is HOE ? Can HOE be defined and classified ? Can HOE be quantified ? Should HOE be reflected in design codes and criteria ?

During this project, Human and Organization Errors (HOE) in design and construction of ship structures were defined and classified. Relevant case studies involving marine and non-marine structures and systems were summarized. Qualitative and quantitative processes for evaluating the incidence and effects of HOE were developed and illustrated. The impacts of HOE on design guidelines were studied, and alternatives for the managment of HOE in the design and construction of ships were addressed.

Particular attention was given to how considerations of HOE should be incorporated into an Load and Resistance Factor Design (LRFD) guideline for ship structures being developed under the auspices of the SSC. Organization, ship designer, written guideline, and computer software aspects were addressed. Specific recommendations were made regarding what should be done in development of the LRFD guideline to address HOE considerations.

This project defined "quality" in ship structures as the realization of the combination of desirable serviceability, safety (reliability), durablity, and compatability (schedule, economic, environmental). This project identified how Total Quality Management (TQM), Quality Assurance (QA) and Quality Control (QC), the ISO 9000 Quality Standards, the International Safety Management (ISM) Code, and Quality Management Systems (QMS) are potentially complimentary approaches that are intended to achieve adequate quality in ship structures.

A Quantified Reliability Analysis (QRA) framework was developed during this project that addresses life-cycle quality in ship structures; how the interactions of individuals, organizations, systems (hardware), procedures (software), and environments affect quality; and how alternative QA and QC life-cycle programs can be evaluated to determine their effectiveness in improving quality. Alternative QA / QC approaches in ship design were suggested. Practical procedures to assist in defining acceptable and desirable levels of quality in ship structures were proposed and illustrated. Responsibilities for achieving quality in ship structures were proposed.

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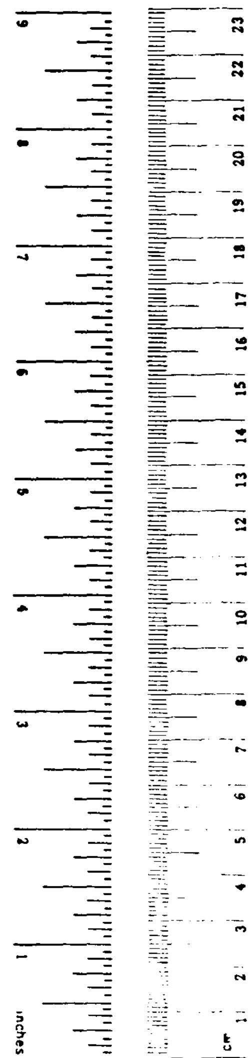
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

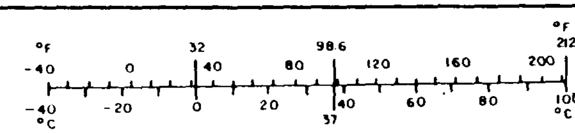
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

Chapter 1

INTRODUCTION

Objective

The objective of this study was to perform a state-of-the-art assessment of the influences of human error on the reliability of marine structures.

This objective was intended to establish guidelines to consider the effects of human errors in design and construction of marine structures and the formulation of structural design criteria.

This project is part of a five-year Ship Structure Committee (SSC)[1] research program to apply reliability technology and develop probability-based design criteria for ship structures. Thus far, this research has addressed a variety of sources of uncertainty and ship design considerations that influence probability based design guidelines for ships. However, Human and Organization Error (HOE) has not been explicitly addressed even though it is the major contributor to lack of reliability in marine structures.

Scope

This project classified and defined HOE in design and construction, summarized relevant case studies, identified qualitative and quantitative processes for evaluating the incidence and effects of HOE, studied the impacts of HOE on design guidelines, and evaluated alternatives for the management of HOE in the design and construction of ships.

The focus of this project was on design and construction of commercial ships with particular attention given to oil, chemical, and bulk carriers.

This project addressed the following key questions:

- What is HOE?
- Can HOE be defined and classified?
- Can HOE be quantified?
- Should HOE be reflected in design codes and criteria?

---

[1]Acronyms are listed and defined in Appendix B

During this study, a review was made of recent developments in consideration of HOE in design and the formulation of structural design criteria. This study included HOE considerations in design of engineered structures such as airframes, space vehicles, nuclear power plants, buildings, ships, and offshore platforms. Recent studies addressing HOE in medicine and in development of computer software were also reviewed.

As a result of this project and allied research on HOE in design, construction, and operations of marine systems [Bea, 1989; Bea, Moore, 1992; Bea, Moore, 1994][2], a practical design and construction oriented HOE classification and characterization system has been developed.

Available background on the effectiveness of different means of quality assurance and control (QA / QC) in design have been summarized. Several such studies have been conducted for the design of conventional building structures.

Guidelines have been developed on how HOE considerations might best be integrated into development of reliability-based design criteria for marine structures. These guidelines address how the incidence of HOE can be reduced by design and how this engineering can influence the incidence of HOE in the construction and operations phases of the life-cycle of the marine structure.

In addition, these guidelines address how the structures themselves can be improved to reduce the effects and consequences of HOE. It is anticipated that the primary improvements will be in the regimes of design for robustness and design for Inspections, Maintenance, and Repair (IMR).

Approach

The scope of work in this project was accomplished by:

1) Performing a literature review, critique, and summary.
2) Developing a structure design oriented classification of HOE.
3) Evaluating the effectiveness of alternative structure design Quality Assurance (QA) and Quality Control (QC) measures.
4) Developing and illustrating the quantification and analyses of HOE.
5) Developing guidelines for consideration of HOE in structure design and criteria.

[2]References are listed in Appendix A

Summary

The following summarizes the answers to the key questions posed at the beginning of this project.

• What is HOE ?

Human error is a departure from acceptable or desirable practice on the part of an individual that can result in unacceptable or undesirable results. *Human error refers to a basic event involving a lack of action or an inappropriate action taken by individuals that can lead to unanticipated and undesirable quality.*

Organization error is a departure from acceptable or desirable practice on the part of a group of individuals that can result in unacceptable or undesirable quality. Organization errors have a pervasive influence on human errors.

Quality in a ship structure has four inter-related key attributes: serviceability (ability to perform intended functions), safety (freedom from harm), durability (freedom from unanticipated maintenance), and compatibility (meets schedule, cost, and environmental requirements).

Human errors develop from a complex variety of influences (Figure 1.1). Individuals acting alone or in teams can make errors. They can be influenced or induced to make errors by organizations, procedures (software, instructions), systems (physical components), and environments (external, internal). There are error producing potentials not only within each of these components, but as well at their interfaces. For example, an individual can misunderstand the goals and objectives of the organization or misinterpret the instructions incorporated into procedures.

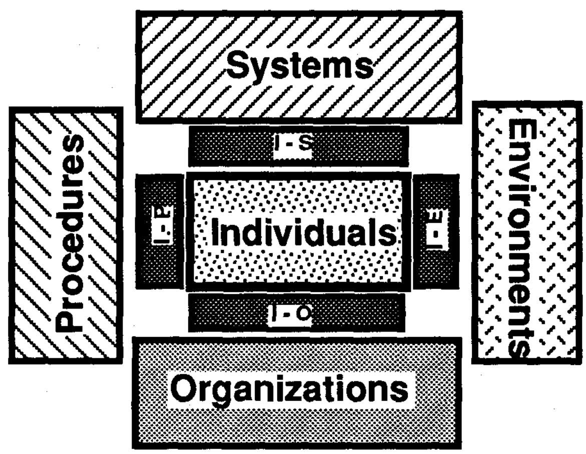


Figure 1.1 - Components and interfaces that can lead to human errors

• Can HOE be defined and classified ?

Yes, human errors can be defined and classified in a variety of ways (e.g. action class, mode, mechanism, effect). The classification and definition needs to be appropriate for a particular descriptive or analytical purpose.

In one scheme HOE can be organized into two categories: 1) those that develop from "states," and 2) those that develop from "actions." States are

those influences that induce individuals, teams, and organizations to make errors. Incentives, environment, and information are some of the primary factors that influence state determined errors. Lapses or slips, mistakes, and unsafe acts are the primary factors that influence actions determined errors. A slip or error of omission is a human error in which what is performed was not intended. A mistake is a human error where the intention was erroneous and was purposefully executed. Unsafe acts are unreasonable or unlawful actions (violations). States can lead to human error in actions, and actions can lead to undesirable states.

Figure 1.2 summarizes the classification of human (individual) errors developed during this project to describe and evaluate the effects of such errors on the design and construction of ship structures.

Human errors can develop as a result of influences from groups of individuals - organizations. Figure 1.3 summarizes the classification of organization errors developed during this project to describe and evaluate the effects of such errors on the design and construction of ship structures.

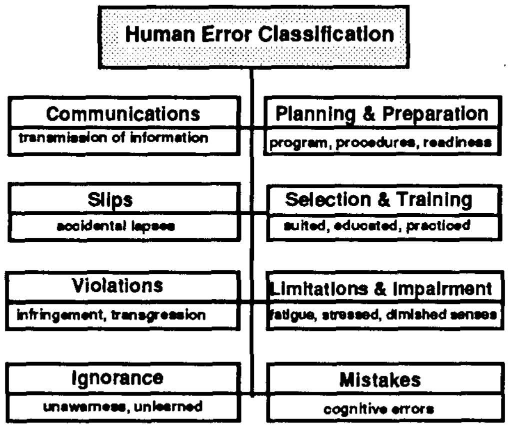


Figure 1.2 - Human errors

- **Can HOE be quantified ?**

Yes, if and as desirable, HOE can be quantified. There are two complimentary approaches to the quantification of HOE in design and construction operations. The first is based on the use of objective data that has been gathered on the incidence of HOE in design and construction activities.

The second is based on the use of expert judgment. Objective data can be developed by the direct gathering of data on the job of interest, information from similar jobs, real-time simulations or experiments with the actual tasks. Subjective data can be derived from extrapolations of objective data and the scaling of expert judgment.

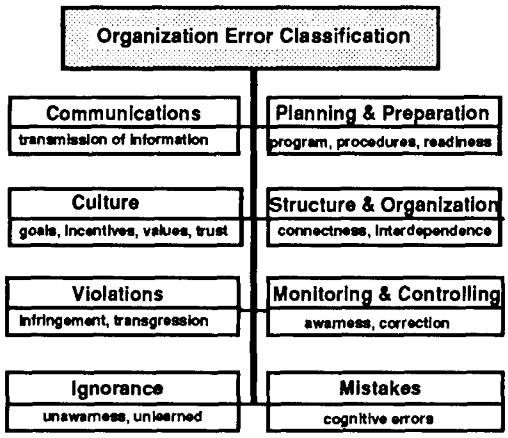


Figure 1.3 - Organization errors

This study has not identified any well organized, long-term effort in which a substantial body of objective data has been developed on HOE in design and construction activities. Some information is available for some types of activities (Figure 1.4).

The tests that have been performed indicate that human performance reliability is influenced dramatically by the "pressure" of performance (Figure 1.5). Pressure results from the combination of psychological stress, task unfamiliarity and complexity, intensity of distractions, limited time, and cognitive impairments. Training, personnel selection, and task complexity reduction, and provision of sufficient time to perform tasks can have important effects on performance reliability.

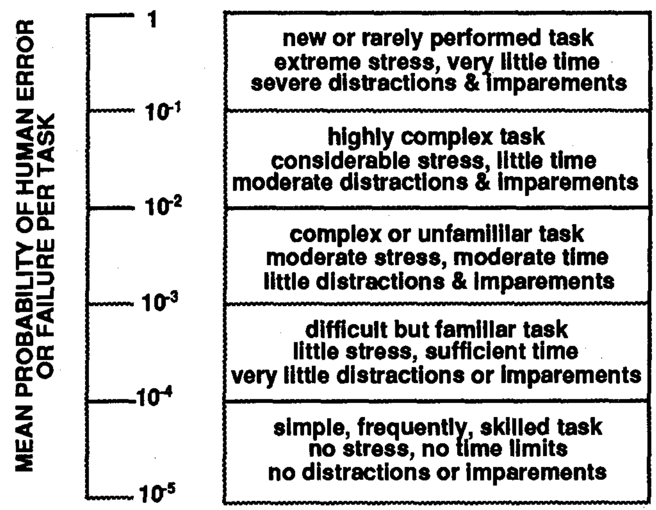


Figure 1.4 - General task human error probabilities

The quantitative information that is available is extremely valuable in that it provides a place to start the processes of quantification. However, primary reliance in making quantification of HOE in design and construction must be placed on the use of expert judgment.

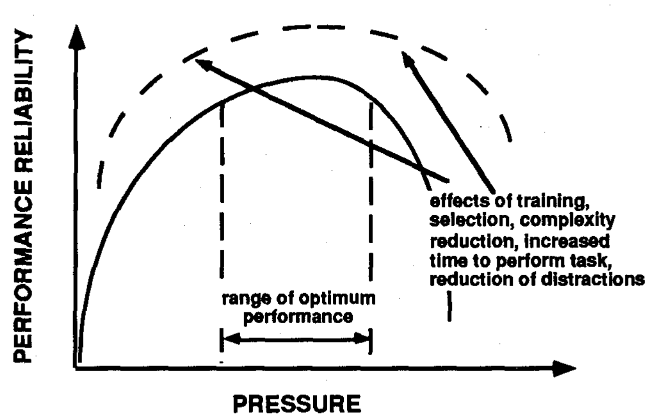


Figure 1.5 - Effects of pressure on human performance

The fundamental purpose of quantitative evaluations based on results from analytical models is not prediction. The fundamental purpose is to provide a disciplined framework with which one can describe and analyze "systems". The objective of these analyses is to make assessments of the potential benefits and costs associated with alternative measures that can improve the quality of ship structures. The objective of these analyses is to provide insights on how best to improve the quality of ship structures and to optimize the use of the resources that can be made available to improve quality.

The desire or requirement for quantitative evaluations and analytical models should not be allowed to become an impediment to improving the quality of ship structures. The focus of the efforts should be to empower those that have responsibilities for achieving quality. Engineers generally have a powerful ability to develop quantitative analytical models. However, they generally also have a weakness in mistaking results from these models for reality.

• Should HOE be reflected in design codes and criteria

Yes, HOE should be reflected in ship structure design codes and criteria in two primary ways. First, in the form of explicit and defined Quality Assurance and Quality Control (QA / QC) measures (Figure 1.6). Second, in the form of explicit and defined measures to make the ship structure less likely to promote errors during its design, construction, and operation, and to make the ship structure more tolerant of the human errors and accidents that can occur during the life of the ship.

There are three primary strategies to incorporate HOE considerations in design codes and criteria:

1) fault avoidance (prevention) - measures intended to lower the difficulty of tasks to be performed by humans and to increase their abilities to perform the tasks.

2) fault detection and removal - provisions for checking, inspecting, independent verifications, and providing measures for correction of faults and flaws when they are found.

3) fault tolerance - design for defect and damage tolerance (robustness in the structure system).

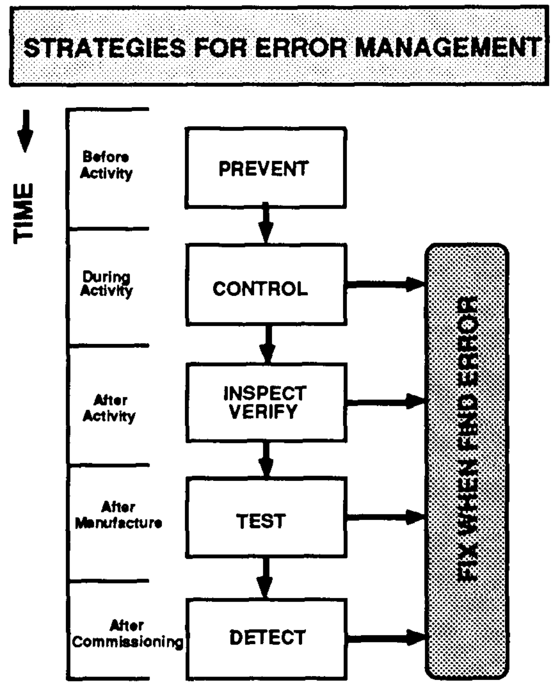


Figure 1.6 - QA / QC life-cycle activities

This study has not indicated that it is effective or efficient to attempt to defend against HOE by employing larger loading factors or smaller resistance factors in the design process. It is much more effective and efficient to manage HOE problems at their sources, i.e., to utilize available resources to reduce the incidence and effects of HOE.

Prevention of HOE is a primary strategy that should be reflected in design codes and criteria. This is the essence of Quality Assurance. Such prevention addresses the accountability and responsibilities of quality in the design and construction of commercial ship structures. These responsibilities are suggested in this report.

Prevention also addresses the qualifications and training of those that design and construct ship structures, the formation of quality oriented design and construction teams, the elimination of unnecessary complexity in design

codes and construction procedures, and the verification and validation of guidelines, procedures, and software used to design ships.

It is important to recognize that HOE can be reduced. However, it is equally important to recognize that HOE can not be eliminated. Thus, ship structure systems should be designed that will be tolerant of the defects and damage that can arise because of "residual" HOE in design, construction, and operation. Ship structure design guidelines that will explicitly consider and address design of error tolerant (robust) structures is an important area for future development.

Report Contents

In the next chapter of this report, the relationships of quality and quality management will be examined in the contexts of TQM (Total Quality Management), the ISO (International Standards Organization) Quality Standards, and QA / QC activities. Engineering and construction activities which can promote quality in ship structures will be discussed.

Chapter 3 develops the interfaces between quality and reliability of ship structures. A life-cycle reliability - quality formulation is proposed in which serviceability, safety (capacity), durability, and compatibility are explicitly addressed. Risk and risk management are discussed in the context of decisions that must be made regarding investments to achieve quality in ship structures.

Chapter 4 discusses QA and QC and the cost / competitive aspects of achieving adequate and acceptable quality in ship structures. Cost - benefit tradeoffs and other approaches to define equitable balances between quality and costs are discussed and illustrated.

Human errors have been studied formally for several decades as they influence the quality of non-marine structures. A substantial background has been developed to address human factors in activities such as operations of nuclear power plants and the U. S. Navy nuclear powered aircraft carrier operations. A substantial body of technology has been developed that has direct applications to marine structures. Chapter 5 reviews highlights of this background.

It has been only relatively recently that there has been a general recognition of the importance of human factors in the quality of marine structures. Historic causes of unsatisfactory quality in marine structures are reviewed in Chapter 6. Several recent examples of problems with insufficient quality in marine structures are reviewed.

Based on the background developed in Chapter 5 and the first part of Chapter 6, a classification of the causes of human (individual), organization, system (hardware), and procedures (software) errors is developed and dis-

cussed. This classification becomes the basis for the qualitative and quantitative evaluation processes that are developed in Chapter 8 and illustrated in Chapter 9.

Chapter 7 defines and discusses general alternatives for the management of human errors in the design and construction of ship structures. Of particular importance in this chapter are the organizational aspects that should be addressed to achieve adequate quality in ship structures.

Chapter 8 discusses three complimentary approaches to the evaluations of HOE in design and construction of ship structures. Qualitative ranking and rating methods are discussed and illustrated. Such methods have found substantial applications in the operations of offshore platforms. Next, quantitative PRA (Probabilistic Risk Analyses) are discussed. Such methods have found substantial applications in operations of nuclear power plants and some applications in the design, construction, and operation of offshore platforms. There have been some exploratory developments in their application to operations of ships.

The third approach discussed in Chapter 8 is a mixed qualitative - quantitative method that might best be described as a Safety Indexing Method. This approach has been widely applied to a variety of non-marine structure and equipment systems. This approach has been applied to two marine structure problems: fires and explosions on offshore platforms and ship operations. Because of its potential application in future developments in design and construction of ship structures, the two marine Safety Indexing Methods have been summarized in Appendix C.

Chapter 9 contains several applications of the foregoing developments to evaluation of HOE effects on the design of marine structures. The first sections in Chapter 9 identify the principal activities and influences involved in the design and construction of ship structures. Next, based on the general ship design process developed, the PRA approach summarized in Chapter 8 is developed formally as it applies to the design of ship structures.

Chapter 9 contains summaries of three example applications. The first is an example that addresses HOE in a Finite Element Analysis (FEA) of a critical part of an offshore platform. Quantitative assessment of the effects of improving parts of the design process are illustrated. A PRA application to the design of an offshore platform structure is summarized in Appendix D.

Chapter 9 then addresses two ship structure design examples that concern design of a class of single hull tankers. The first example addresses HOE aspects of the fatigue durability in the Critical Structural Details (CSD). The second example addresses HOE aspects concerned with the FEA of the CSD in these ships. Both examples involve qualitative and quantitative assessments. Both examples illustrate the evaluation of alternatives intended to improve the quality of the design of the CSD.

Chapter 10 summarizes what has been learned during this project as it applies to an LRFD guideline for ship structures being developed under the auspices of the SSC [Mansour, et al., 1993]. Organization, ship designer, and written guideline aspects are addressed. Specific suggestions are made regarding what should be done in development of the design guideline to address HOE considerations.

Chapter 11 identifies key research and development efforts that should be considered if this work is to be continued. These efforts address education, design, construction, and operations aspects of ship structures.

Chapter 12 summarizes the principal developments from this project. Conclusions concerning how what has been learned should be applied to help improve the quality of ship structures are summarized.

Appendix A contains a listing of all references cited in this report. Appendix B contains a listing of the primary acronyms used in this report. Appendix C contains a summary of the two marine structure related Safety Indexing Methods. Appendix D contains a summary of the PRA application to design of an offshore platform structure.

Acknowledgments

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Mr. Aaron Salancy (Graduate Student Researcher, NAOE UCB, presently employed by NASCO) performed and documented the example analyses of alternative strategies for the management of HOE in design of ships that are contained in Chapter 9 [Salancy, 1994b].

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Chapter 2

QUALITY & QUALITY MANAGEMENT

Quality

Quality is defined in this report as freedom from unanticipated defects. Quality is fitness for purpose. Quality is meeting the requirements of those that own, operate, design, construct, and regulate ship structures. These requirements include those of serviceability, safety, compatibility, and durability [Matousek, 1990] (Figure 2.1).

Serviceability is suitability for the proposed purposes, i.e. functionality. Serviceability is intended to guarantee the use of the system for the agreed purpose and under the agreed conditions of use.

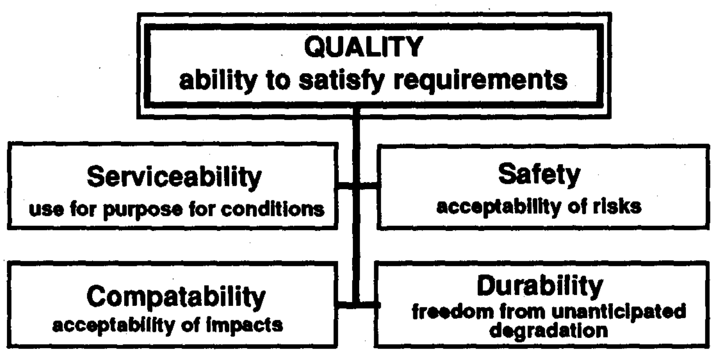

Figure 2.1 - Attributes that constitute quality in ship structures

Safety is the freedom from excessive danger to human life, the environment, and property damage. Safety is the state of being free of undesirable and hazardous situations. The capacity of a structure to withstand its loadings and other hazards is directly related to and most often associated with safety.

Compatibility assures that the system does not have unnecessary or excessive negative impacts on the environment and society during its life-cycle. Compatibility is the ability of the system to meet economic and time requirements.

Durability assures that serviceability, safety, and environmental compatibility are maintained during the intended life of the marine system. Durability is freedom from unanticipated maintenance problems and costs.

Quality has been defined by Stena [1992] as:

"An attitude and culture which adopts a never-ending journey of meeting customers' needs and expectations through continuous improvement by fully trained and empowered employees."

Quality obviously has different meanings for different people. In this report, the term quality as applied to design and construction of ship structures will be taken to be:

freedom from unanticipated defects in the serviceability, safety, durability, and compatibility of the ship structure.

Quality Management Systems

In recent years, a wide variety of processes, procedures, and philosophies intended to improve and achieve adequate quality in goods and services have been developed and implemented. The ones that will be discussed here include Total Quality Management (TQM), Quality Assurance (QA), Quality Control (QC), and ISO (International Standards Organization) quality standards. These components can be viewed as building blocks of a Quality Management System (QMS).

Figure 2.2 - Relationships of TQM, QA, QC, and ISO quality standards

At the outset, it is important to recognize that these processes, procedures, and philosophies are related to the same objective (Figure 2.2). They represent complimentary parts of activities that are intended to help achieve adequate and acceptable quality. These are the building blocks that can help achieve quality.

Total Quality Management

TQM has its roots founded in an effort that dates back to the early 1900's. Walter Shewhart, a scientist at Bell Laboratories, proposed that successful scientists follow a general pattern to improve knowledge with new ideas. First, they plan a way to test their ideas through experimentation. Second, they do their experiments. Third they check the measured results against the planned results. Fourth, they act on the results. If their ideas are not verified, or not verified completely, they start over by modifying their ideas. But, if their ideas are validated, these ideas become added to the body of scientific knowledge. This scheme became the plan-do-check-act process of continuous experimentation.

In 1924, W. E. Deming was a young graduate student intern at Bell Laboratories. He worked for Shewhart and documented the "Shewhart Cycle of Continuous Improvement." In the 1950's, Deming taught the Japanese how to apply the continuous improvement cycle to all forms of work. The philosophy proved so successful that it found its way back into U. S. industry in the 1980's [Deming, 1982].

Deming founded his philosophy of Total Quality Management (TQM) on the fourteen points summarized in Table 2.1

Table 2.1 - The Deming fourteen points of TQM

1. constancy of purpose 2. adoption of new philosophies 3. elimination of inspections 4. don't buy on price alone 5. quality improvement is never ending 6. institute on the job training 7. substitute leadership for supervision and management 8. drive out fear and create confidence	9. break down barriers 10. eliminate slogans and targets 11. eliminate management by objectives and quotas 12. remove barriers to pride and quality 13. institute a program of education and self improvement 14. do it and re-do it as a continuous process of improvement in quality

Total Quality Management (TQM) is a management philosophy: a way of thinking and working [Adrian, 1992]. It has three main themes:

- Customer satisfaction,
- Participative management, and
- Ongoing improvement.

The focus of TQM is on improving quality by removing defects and solving problems [Oswald, Burati, 1992]. TQM focuses on envisioning the company as a linkage of processes, a coherent system of people and procedures.

TQM promotes the following key management practices and activities:

- Do it right the first time.
- Minimize production variations and risks.
- Emphasize problem solving through participative management teams.
- Compare quality and performance results with a predetermined and measurable standard.
- Provide continual training and education aimed at quality improvement.

Quality Assurance & Quality Control

Quality Assurance and Quality Control can be categorized as parts of Quality Management Systems (QMS). QMS are systems of formal documented practices used by an organization or team to measure, report, and control the quality of its goods and services [Puri, 1991]. QMS establishes ways to meet the stated and implied requirements.

Quality Assurance (QA) are those practices and procedures that are designed to help assure that an acceptable degree of quality is obtained. QA is focused on prevention of errors. QA consists of system oriented planned actions to achieve quality, corrective processes, and prevention of problems.

Quality Control (QC) is associated with the implementation and verification of the QA practices and procedures. QC is intended to assure that the desired level of quality is actually achieved. QC is focused on inspection, reaction, identification of errors, rectification, rework, and correction.

ISO Quality Standards

The International Standards Organization (ISO) 9000 series of international quality standards [ISO, 1994, 1994a] and the related standards [British Standards Institution, 1990; Norwegian Standards, 1990] are sets of requirements for critical elements in documented business / industrial systems. These standards touch on topics from management review and design control to statistical techniques.

The ISO Standards have their roots founded in a much earlier set of standards that were developed by the U. S. Military during the second World War. The Military standards were further developed and detailed in Europe during the 1970's and 1980's. Both the British [British Standards Institution, 1990] and the Norwegians {Norwegian Standards, 1990] developed comparable standards that were intended to help achieve desirable degrees of quality in primarily manufactured systems. Later, these standards were harmonized and integrated into a set of harmonized European standards. The formation of the European Economic Consortium resulted in development of the ISO. The ISO system of quality standards were an early result that were published in the late 1980's.

ISO 9000, "Quality Management and Quality Assurance Standards - Guidelines for Selection and Use" is the introduction to the ISO quality system (ISO, 1994a). It explains fundamental quality concepts; defines key terms; and provides guidance on selecting, using, and tailoring the other standards to fit specific needs. Table 2.1 summarizes the key elements that comprise ISO 9000 [Moore, Roberts, 1994].

Table 2.1 - Components of ISO 9000

- Management Responsibility
  - Quality Policy
  - Responsibility and authority
  - Verification resources and personnel
  - Management representation
  - Management review
- Quality system
- Contract review
- Document control
- Purchasing
- Purchasers supplied product
- Product identification and tractability
- Process control
- Inspection and testing
- Inspection, measuring and testing equipment
- Control of non-conforming products
- Corrective action
- Handling, storage, packaging, and delivery
- Quality records
- Internal quality audits
- Training
- Statistical techniques & analyses

ISO 9001, "Quality Systems - Model for Quality Assurance in Design / Development, Production, Installation, and Servicing, covers all of the elements found in 9002 and 9003 (ISO, 1994b). It provides additional details and adds requirements for design controls and after commissioning servicing.

ISO 9002, "Quality Systems - Model for Quality Assurance in production and Installation," deals with the prevention, detection and correction of problems during production and installation. It addresses manufacturing aspects such as purchased materials, work in process, record keeping, training, and auditing.

ISO 9003 "Quality Systems - Model for Quality Assurance in Final Inspection and Test," provides requirements for sorting acceptable and non-acceptable products before transportation and commissioning.

ISO 9004, "Quality Management and Quality System Elements - Guidelines," is intended for organizations that are initiating their quality management programs. The 9004 standard is intended to help organizations develop a better grasp of the principles of quality management and the needs of their organizations and customers. The 9004 standard is the foundation for the ISO quality developments. ISO 9001, 9002, and/or 9003 are then selected to establish the particulars of a quality system. The 9004 standard embodies the development of TQM in a given organization.

It should be understood that the ISO guidelines are essentially a system for QA. The ISO guidelines do not assure quality. It is the combination of QA, QC, TQM, and "beyond TQM" that is intended to assure quality.

Beyond TQM

The background developed before and during this project on the management of Human and Organization Errors (HOE) in the design, construction, and operation of marine systems clearly indicates that there is something beyond TQM, QA, QC, and the ISO Standards that should be added to help advance achieving quality in marine systems. The author has designated these activities as TQE (Total Quality Engineering), TQC (Total Quality Construction), and TQO (Total Quality Operations).

Figure 2.3 indicates that there are two principal types of "influences" that can have profound effects on the quality of a marine system during its life cycle. Both the environment (or environments) and humans are clearly involved in determining if a system will have adequate serviceability, safety, durability, and compatibility.

There are clearly controllable and uncontrollable aspects of both of these sets of influences. Quality managers are most interested in the controllable aspects. The uncontrollable aspects must be relegated to residual, inherent elements that can not be reasonably managed and must be accepted as reality. In many cases, it is difficult, if not impossible to fully identify or detail the inherent or residual aspects.

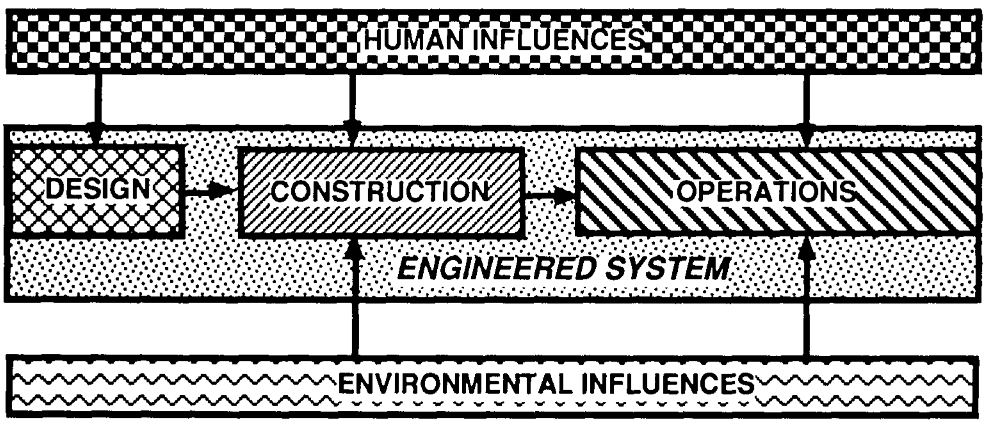

Figure 2.3 - Human and environmental influences on the life cycle quality of a marine system

TQM is a management philosophy intended to achieve quality. It is directed at the people and organizational elements (Figure 2.4). TQM combines excellence in planning (determining the future goals and paths to those goals), organizing (to achieve the future goals), leading (to assure the future goals are reached), and controlling (to monitor and re-direct as required to reach the future goals).

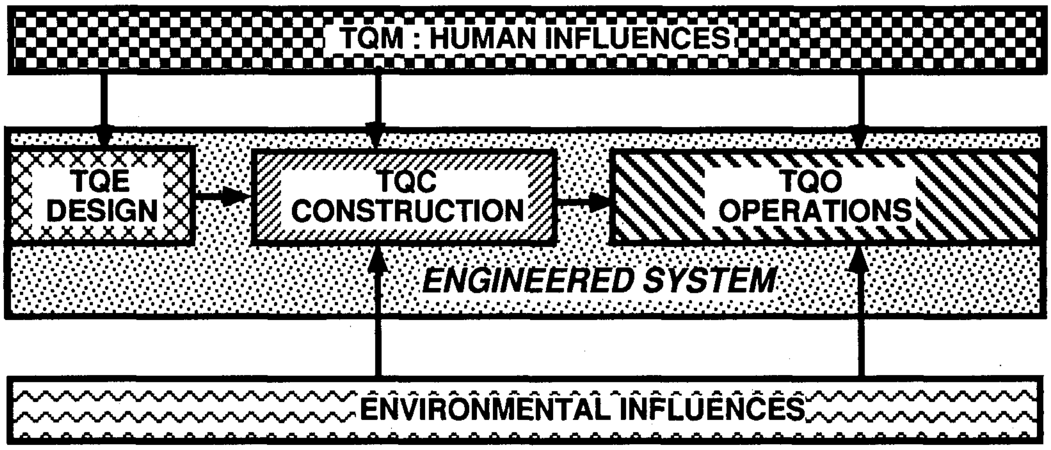

Figure 2.4 - TQM and "down-stream" Total Quality Engineering, Total Quality Construction, and Total Quality Operations

QA, QC, and the ISO quality standards are proactive and reactive processes and activities that are intended to help achieve quality. These are elements of a QMS.

In the author's experience what is lacking in these elements of a QMS is a proactive and reactive, comprehensive and detailed focus on the "system" and its "life-cycle quality". The system includes "hardware" (structure, equipment, facilities), "software" (instructions, procedures, processes), and the "people-ware" (individuals, teams, organizations, and societies). The life-cycle includes design, construction, and operations (including maintenance).

TQE is the activity of analyzing design, construction, and operations (including maintenance) systems, determining how best to achieve the desirable levels of quality in these systems, and then engineering systems (hardware, software, and people ware) to achieve the desirable levels of quality. TQE is not the traditional process of engineering a structure, facility, or piece of equipment. It is beyond this process. It is both up-stream and down-stream of this traditional process. It examines the guidelines, context, and constraints associated with a marine system and provides information and insights to help achieve a desirable level of quality during the life-cycle of a marine system. It goes beyond hardware.

TQE should develop insights and information on the alternatives associated with different ways to achieve quality and the costs and benefits associated with different levels or degrees of quality. TQM should evaluate these alternatives and determine what levels of quality should be developed during the life-cycle phases of a marine system.

TQC is the activity of analyzing construction systems for a particular marine structure to be built in a particular facility at a particular time with a particular construction "infrastructure" and then determining how best to achieve the desirable levels of quality in the constructed product.

TQO is the activity of analyzing the operations system for a particular marine structure to be operated in a particular environment and location at a particular point in time with a particular operations "infrastructure" and then determining how best to achieve the desirable levels of quality in the operated marine system.

An example of TQO is the International Safety Management (ISM) Code [International Chamber of Shipping, 1993; International Maritime Organization, 1993]. This Code is discussed in further detail in Chapter 6. The objective of the ISM Code is to establish an international standard for the safe management and operation of ships. This objective is accomplished by setting rule for the organization of company management in relation to safety and pollution prevention and for the implementation of a Safety Management System (SMS). The ISM Code is intended to re-orient the current approach to regulatory compliance from the industry's passive defect notification and correction response mode to an aggressive approach to safety. Under such a proactive approach, potential discrepancies are resolved by the companies themselves, before they can become significant safety or environmental problems [Moore, Roberts, 1994].

TQC and TQO both represent down-stream updating, revision, and detailing of the insights and information developed by TQE. If quality is to be achieved, it must be a continuous process throughout the life-cycle. If quality is to be achieved, it must not be regarded as a 'fad'. In addition, a 'compliance' or "I will do what I am told or can get by with" attitude must not be allowed to develop if quality is to be realized.

An important part of TQE, TQC, and TQO is the use of continuous monitoring and controlling systems to detect, analyze, and report quality variances [Bea, 1992, 1993; Moore, Bea, 1993]. Such monitoring systems have several purposes. The first purpose is feed-back on the causes and locations of quality variances. Timely updating of QA measures and QC correction should be a result. The second purpose is the development of "early warning" and "near miss" systems. Trends in quality variances and trends in the types and frequencies of near misses can provide important information to allow detection of unfolding or evolving quality problems. A life-cycle Ship Structural Integrity Information System (SSIIS) is being developed for this purpose [Schulte-Strathaus, Bea, 1994].

Most importantly, TQM, TQE, TQC, and TQO should provide adequate and timely "empowerment" to those that have direct responsibilities for quality. These are the individuals and teams with their "hands on the wheels." These are the individuals and teams on the "front-lines" of design, construction, and operations activities associated with marine systems.

Empowerment includes clearly identified responsibilities, goals, and adequate resources (time, money, materials, manpower, knowledge) to achieve quality. Empowerment includes a requirement and demand for integrity to achieve quality. Empowerment includes a requirement for intimate involvement, leadership and direction of TQE, TQC, and TQO activities.

If TQE, TQC, and TQO are to have beneficial, realistic, and timely results, then the driving forces to achieve quality must come from the "front lines." The initiative, direction, and implementation must be centered on the front line operators. Analysts and "theoreticians" should be involved in supporting, assisting, and facilitating roles. Extensive hands-on experience in the details of the particular design, construction, and operation being addressed is the most essential ingredient in the processes. TQE, TQC, and TQO are not "numbers games." TQE, TQC, and TQO are an attempt to achieve quality in the face of a hostile environment (the sea) and in the face of many and great uncertainties. Insufficient knowledge and experience behind TQE, TQC, and TQO efforts results in "meddling" or "tinkering" with a system. The potential benefits of the efforts will not be realized and "bad attitudes" will be develop regarding such efforts.

Experience

During the past 10 years, there has been a series of good and bad experiences in the implementation of QMS. A recent study conducted by Loney and Ramierz [1994] involved a survey based on 63 U. S. firms that had attempted to implement QMS during this time period. These involved industry - manufacturing (29 %), services sector (62 %), and military (9 %) organizations. The sizes of the organizations ranged from less than 100 employees (19 %), to 100 to 500 employees (22 %), to more than 500 employees (59 %).

Table 2.2 summarizes the Tier 1 (ranked 1 to 10) and Tier 2 (ranked 11 - 20) activities that the survey indicated to be most important in determining the success of QMS implementation.

The survey identified the single most important requirement for successful implementation of QMS was *management commitment*. The major reason for failure of QMS implementation was lack of genuine and sufficient management commitment.

Table 2.2 - Importance of QMS activities

Tier 1
• Management commitment • Customer satisfaction • Clear vision statement • Cultural change • Education • Participative management • Strategic quality planning • Goal clarity • Error prevention • Top management steering
Tier 2
• Timely problem solving • Measurement of quality • Correct problem identification • Goal setting • Recognition programs • Quality improvement teams • Partnerships • Project improvement process • Measurement & control • Monetary resources

Management commitment included a clear vision statement (goal clarity) and provision of sufficient resources (qualified manpower, money, time) to achieve quality.

Management commitment addressed the capability and willingness of leaders to define and implement QMS. The capability aspects addressed recognition of organization vulnerabilities, an understanding of business and corporate environmental challenges, an objective assessment of current capabilities, demonstration of leadership skills, and the emotional maturity required for risk taking.

The willingness aspects addressed overcoming traditional assumptions about employees, relinquishment of the investment in the status quo, *relinquishing traditional power strategies and practices,* persistence, integrity, and maintaining a focus on transition outcomes.

Experience of these organizations indicates that the most important thing needed for a successful QMS is top-down management commitment, leadership, and integrity. This experience indicates that a successful QMS will not be allowed to become a "paper chase" where processes are allowed to subvert the activities needed to achieve quality.

Summary

Quality is freedom from unanticipated defects. Quality is fitness for purpose. Quality is meeting the requirements of those that own, operate, design, and construct marine systems.

Quality is comprised of four primary attributes: serviceability (do what it is supposed to do), safety (does not pose undue risks), durability (free from unanticipated maintenance), and compatibility (meets time, monetary, and environmental requirements).

Quality requires a permeating philosophy. That philosophy can be represented by TQM. TQM is comprised of planning, organizing, leading, and controlling to achieve quality during design, construction, and operation of a marine system. It is focused on processes of continuous improvement. It is focused on integrity on the parts of those that own, operate, design, build, and regulate marine systems.

Quality requires a permeating activity throughout the life-cycle of a marine system. That activity can be represented by QMS. QA and QC are components of QMS. A focus is on QA: "an ounce of prevention is worth a ton of cure." QC requires continuous vigilance. QC requires timely feed-back to improve QA.

The ISO quality standards are one form of QA. The ISO quality standards are not QC.

There is an important need to focus on the details and comprehensive nature of marine systems. TQE, TQC, and TQO represent activities that are intended to provide such a focus during the evolution and life-cycle of marine systems.

All of this effort to achieve quality should be directed at empowerment of those individuals and teams that design, construct, and operate marine systems. From an engineering standpoint, the objective is not to perform analyses, produce numbers, or technical reports and papers. The objective is to provide timely insights on how best to achieve quality. TQE starts the cycle, it is further detailed and updated by TQC (with feedback to TQE on how to help improve quality), and then it is continuously detailed and updated by TQO (with feedback to TQE and TQC on where there are problems and how quality can be improved).

Quality requires commitment. Quality requires integrity. Quality is not quick, easy, or free. The initial costs associated with achieving quality can be repaid many times over by the costs not realized due to insufficient or unacceptable quality. So, quality can be "free".

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Chapter 3

QUALITY, RELIABILITY, RISKS, & DECISIONS

Reliability

Reliability is closely related to quality. *Reliability is defined in this report as the probability that a given level of quality will be achieved during the design, construction, and operating life-cycle phases of a marine structure.*

Reliability is the likelihood that the system will perform in an acceptable manner. Acceptable performance means that the system has desirable serviceability, safety, compatibility, and durability.

The compliment of reliability is the likelihood or probability of unacceptable performance; the probability of "failure" (Pf).

Success is the ability to anticipate and avoid failure. *Failure is an undesirable and unanticipated outcome; the lack of meeting expected performance; the significant loss of utility.* Experience has amply demonstrated that the single largest factor responsible for failure of marine structures is "human error".

Likelihoods of not realizing a desirable level of quality arise because of a wide variety of uncertainties. During the design phase there is a likelihood of not realizing the intended quality due to causes such as an analytical flaw embedded in a finite element program or an error made in interpreting a design loading formulation. During the construction phase, unrealized quality might be developed by the use of the wrong materials or use of inappropriate alignment and welding procedures. During the operating phase, unrealized quality might be developed by accidental loading from collisions or dropped objects or neglect of planned maintenance of coatings and cathodic protection.

Reliability can be expressed analytically as:

$$Ps = [1-Pf] = P[D \leq C] \tag{3.1}$$

where D is the demand placed on the marine structure system and C is the ability or capacity of the system to meet or satisfy the demand. P [x] is read as the probability that the event [x] takes place. Demands and capacities are quanti-

fied in terms used to define serviceability (e.g. days available for service), safety (e.g. margin between load resistance and loading), durability (e.g. expected life of structure), and compatibility (e.g. expected initial and future costs).

Generally, structural reliability has been defined as the likelihood that the marine structure's capacity is exceeded by the dead, live, and environmental loading [Moan, 1993]. This definition has been criticized because of its limited scope. Conventional structural reliability analysis fails to address the other key issues associated with the quality of the marine structures. The conventional definition fails to address the other key hazards to the quality of the structure that develop during the life-cycle of the structure (design, construction, operation).

Unreliability is due fundamentally to three types of uncertainties [Bea, 1990]. The first is inherent or natural randomness (aleatory). The second is associated with analytical or professional uncertainties (epistemic). The third is associated with errors made by individuals and groups of individuals or organizations (human errors) [Moan, 1993; Bea, Moore, 1991, 1992].

While conventional structural reliability assessments have explicitly addressed the first two types of uncertainty, in general they have not addressed the third category of uncertainty. At best, the third category of uncertainty has been included implicitly. It has been incorporated in the background of data and information that is used to describe the uncertainties and variabilities.

The life-cycle probability of a marine structure not developing a desirable level of quality could be expressed analytically as:

$$Pf = Pf_1 + Pf_2 + Pf_3 + Pf_1\, Pf_2 + Pf_2\, Pf_3 + Pf_3\, Pf_1 \qquad (3.2)$$

where the subscripts 1, 2, and 3 refer to the probability of failure of the marine structure that develop during the design, construction, and operating life-cycles phases of the structure, respectively.

Unreliability that is developed during the design phase could be expressed analytically as:

$$Pf_1 = Pf_{1.1} + Pf_{1.2} + Pf_{1.3} + Pf_{1.1}\, Pf_{1.2} + Pf_{1.2} Pf_{1.3} + Pf_{1.3}\, Pf_{1.1} \qquad (3.3)$$

where the subscripts 1.1,1.2, and 1.3 refer to the probabilities of failure due to concept definition, development of loading, and sizing and detailing the structure, respectively.

Unreliability that is developed during the construction phase could be expressed analytically as:

$$Pf_2 = Pf_{2.1} + Pf_{2.2} + Pf_{2.3} + Pf_{2.1}\, Pf_{2.2} + Pf_{2.2} Pf_{2.3} + Pf_{2.3}\, Pf_{2.1} \qquad (3.4)$$

where the subscripts 2.1,2.2, and 2.3 refer to the probabilities of failure due to fabrication, transportation, and commissioning or installation of the structure, respectively.

Unreliability during the operations phase could be expressed analytically as:

$$Pf_3 = Pf_{3.1} + Pf_{3.2} + Pf_{3.3} + Pf_{3.1}\, Pf_{3.2} + Pf_{3.2} Pf_{3.3} + Pf_{3.3}\, Pf_{3.1} \quad (3.5)$$

where the subscripts 3.1, 3.2, and 3.3 refer to the probabilities of failure due to accidents, maintenance, and environmental conditions, respectively.

Later in this report, after a classification and description system has been developed to permit analyses of HOE effects in design and construction, a similar reliability formulation is developed allow one to explicitly address the key HOE aspects involved in design and construction of marine structures.

Reliability Formulation

Reliability is the likelihood that the system will perform in an acceptable manner. In the context of the design and construction of a ship structural system, reliability will be expressed in this section in two contexts. The first relates to the capacity of the structural system and the second relates to the fatigue or cracking durability of the structural system.

For development of background in reliability technology applied to marine structures the reader is referred to the report by Mansour, et al. [1990], the text by Bea [1990], and the report by Orisamolu and Bea [1993]. Comprehensive texts have been written on this subject and the reader is referred to the texts by Ang and Tang [1975], Madsen, Krenik, and Lind [1986], Melchers [1987], and Henley and Kumamoto [1981] for additional background.

In the context of capacity, the reliability, Psc, of the structural system can be expressed as:

$$Psc = P\,[\text{capacity} \geq \text{loading}] = P\,[R \geq S] \quad (3.6)$$

Capacity refers to the ability of the structural system to sustain the imposed and induced loadings.

In the context of durability, the reliability of the structural system can be expressed as:

$$Psf = P\,[\text{time to cracking} \geq \text{service life}] = P\,[Tc \geq Ts] \quad (3.7)$$

where Tc is the time (cycles) to cracking in a Critical Structural Detail (CSD) in a ship structural system and Ts is the intended or design service period for the ship.

The compliment of reliability is the probability of failure, Pf (Pf = 1 - Ps). The reliability can be expressed as follows:

$$Ps = \Phi [\beta] \tag{3.8}$$

where Φ is the standard cumulative normal distribution and β is the Safety Index. The Safety Index can be related approximately ($1 \leq \beta \leq 3$) to Ps as:

$$Ps = 0.475 \exp -(\beta)^{1.6} \tag{3.9}$$

or very approximately:

$$Ps \approx 1 - 10^{-\beta} \tag{3.10}$$

For the purposes of illustration, let it be presumed that the probability distributions of R, S, Tc, and Ts are Lognormal. Such a distribution is frequently an excellent characterization for these parameters. Then:

$$\beta c = \frac{\ln R_{50} / S_{50}}{(\sigma_{\ln R}^2 + \sigma_{\ln S}^2)^{0.5}} \tag{3.11}$$

and:

$$\beta f = \frac{\ln Tc_{50} / Ts}{\sigma_{\ln Tc}} \tag{3.12}$$

The subscript variables, X_{50}, refer to the 50th percentile or median values of the variables. This is a measure of the central tendency (or center of gravity) of the probability distributions. $\sigma_{\ln X}$ refers to the standard deviation of the logarithm of the variables. This is a measure of the dispersion or variability (or moment of inertia) of the probability distributions.

Given this formulation, the primary reliability considerations are the "central tendency" ratios R_{50} / S_{50} and Tce_{50} / Ts, and the uncertainty measures $\sigma_{\ln R}$, $\sigma_{\ln S}$, and $\sigma_{\ln Tc}$. The central tendency ratios (capacity / demand) can be interpreted as "factors of safety." These ratios will be dependent on the probability level or "return period" used to define the demand quantity.

Capacity Effects

Figure 3.1 shows the variation of the annual Safety Index with the factor of safety. This example is based on the use of a 100-year return period condition for the design loadings, a total uncertainty of $\sigma = 0.5$, and a capacity uncertainty of $\sigma_R = 0.25$. For example, to achieve $\beta c = 3$ (Pfc $\approx$ 1E-3 per year), requires a factor of safety of 1.7.

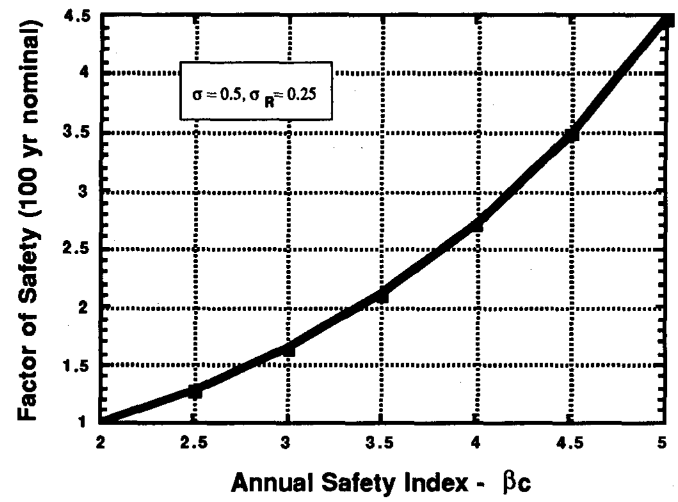

Figure 3.1 - Annual capacity Safety Index as function of the factor of safety

Figure 3.2 shows how an underestimate in the loading - capacity uncertainties can reduce the Safety Index. It is presumed that the "target" or intended value of the Safety Index is $\beta c = 3.0$. A 50 % underestimate in the uncertainty results in increasing the probability of failure by about one order of magnitude.

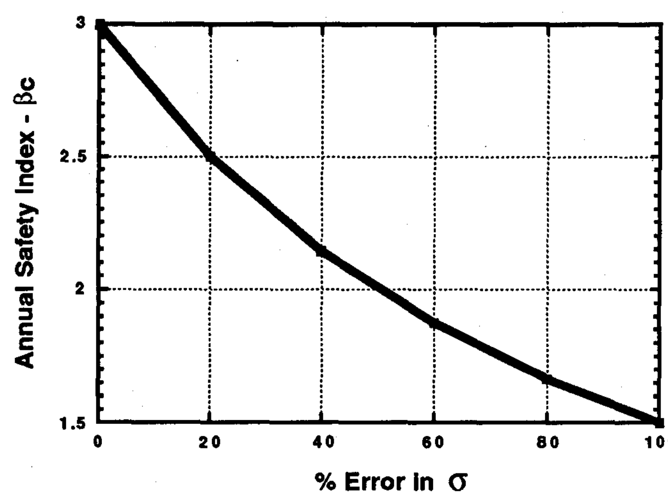

Figure 3.2 - Effects of underestimation errors in the total uncertainty in loadings and capacity on the Safety Index

Underestimation of the loading-capacity uncertainties could occur during either design or construction. During development of the design criteria, there could be an underestimation of the uncertainties associated with either the loadings, capacities, or both . During the construction, due to poor quality control, there could be an increase in the capacity variability over that assumed in development of the design criteria.

Operations could also have affects on both the loadings and capacities. Maneuvering practices in severe weather and maintenance of corrosion protection are examples of operating influences.

There also could be overestimation of the loading-capacity uncertainties. These would lead to more reliability being incorporated into the system than was intended. This would lead to unexpected excess strength and durability in the ship structure. Generally, such an outcome would not be deemed to be undesirable unless the costs associated with the excess strength and durability were found to be excessive. In this discussion, the focus will be on developments that could result in insufficient strength an durability in the ship structure.

Figure 3.3 shows the effects of errors in the central tendency ratio of the ship structure capacity to the loadings. In this case, a 50 % error in the ratio results in much more than an order of magnitude increase in the probability of failure of the structure. The reliability is more sensitive to the central tendency ratio than to the variability.

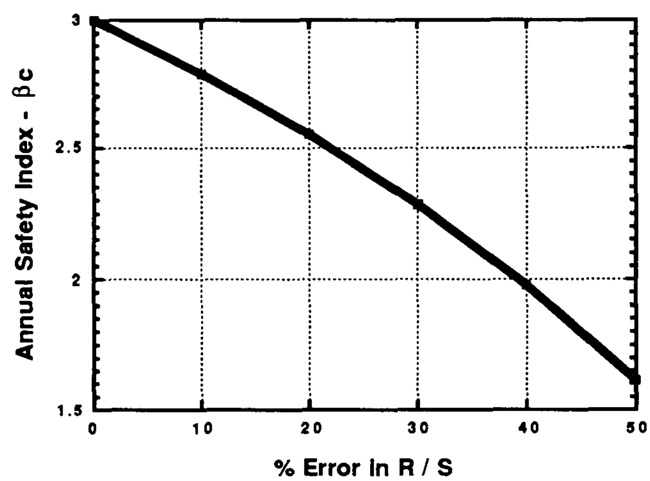

Figure 3.3 - Effects of overestimation errors in the median capacity to loading ratio on the Safety Index

An underestimate of the capacity to loading ratio could develop in several ways. During the formulation of the design criteria, a systematic bias could be introduced that would result in an overestimate of the capacity or an underestimate of the loadings (e.g. ignoring important dynamic effects). During construction, there could be quality control problems such as excessive misalignments or use of lower grade steel that would result in systematically lowering the capacity of the structure.

The importance of these results is as follows. The central tendency capacity to loading ratio has the largest effects on reliability. Therefore, the greatest management efforts should be directed to minimize the possibilities of human errors in activities that could determine this ratio. A close second in this priority would be the uncertainties in the loadings and capacities. Given the generally much greater uncertainties associated with the loadings, management of human errors that could lead to under-estimates in the uncertainties in the loadings would be the next priority.

Durability Effects

Figure 3.4 shows the variation on the annual Safety Index at the end of the service period with the central fatigue cracking durability factor of safety (Tf_{50}/Ts). An uncertainty of the time to cracking of $\sigma_{lnTc} = 1.0$ has been assumed in this example. For these conditions, a central factor of safety of about $Tf_{50}/Ts = 7$ would be required to obtain $Pfc \approx 1E\text{-}2$ per year. In other words, if the design service period were 20 years, the design median time to cracking should be about Tf = 140 years.

Figure 3.4 - Variation in the annual Safety Index with the median factor of safety on the time to fatigue cracking

Based on the previous developments, Figure 3.5 shows the variation of the fatigue cracking Safety Index as a function of service time. The Safety Index at any time, t, can be expressed as follows:

$$\beta f_t = \beta f - \frac{\ln(t / Ts)}{\sigma_{lnTc}} \qquad (3.13)$$

As noted previously, the design Safety Index is reached only at the end of the service life; due to the lack of damage from cyclic loadings probability of fatigue cracking much lower) early in the life of the structure.

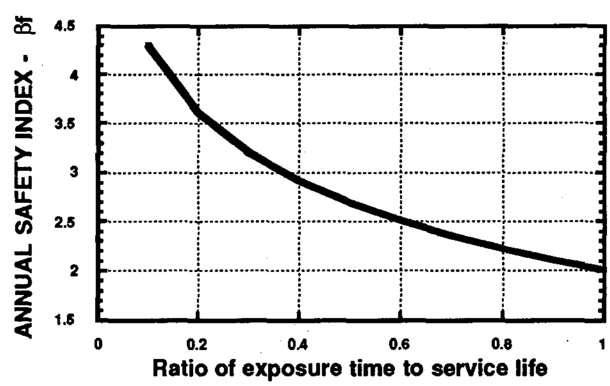

Figure 3.5 - Variation of fatigue cracking Safety Index with exposure time (design Safety Index = 2.0)

Figure 3.6 summarizes the effects on βf of potential underestimation errors in σ_{lnTc}. In this case, a 50 % underestimation, does not result in increasing the probability of fatigue cracking by an order of magnitude. Similarly, as shown in Figure 3.7, overestimating the median time to fatigue cracking by 50 % does not result in increasing the probability of fatigue cracking by an order of magnitude. The two effects are very comparable.

The underestimation in the uncertainty in the time to cracking could have a design source or a construction source (or both). The design underestimation

could be due to insufficient fatigue testing data with which to develop an accurate estimate of the uncertainty or the median time to cracking. The construction effects that would result in an underestimate of the uncertainties or an overestimate in the time to cracking could be due to improper profiling of the welds (weld profile assumed in design and utilized in the fatigue testing not realized) or due to excessive misalignments (introducing secondary bending stresses not accounted for in design).

The almost equal effects on the fatigue cracking Safety Index of the underestimation of uncertainties or the overestimation of time to cracking would indicate equal resources should be devoted to quality assurance and control measures in both design and construction to properly manage the uncertainties in the times to fatigue cracking.

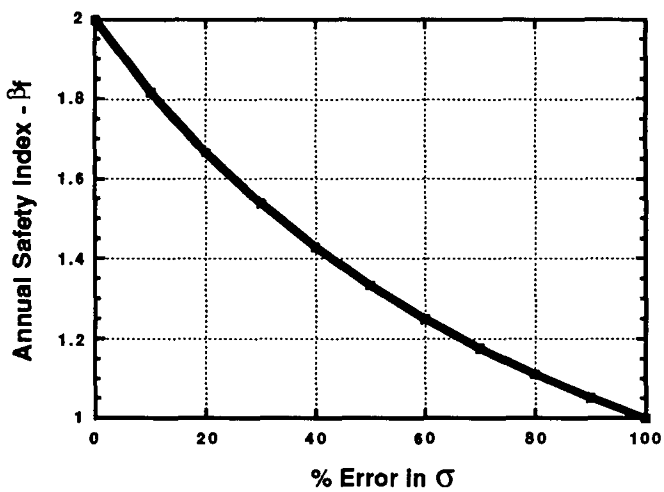

Figure 3.6 - Effects of underestimating the uncertainty of time to fatigue cracking

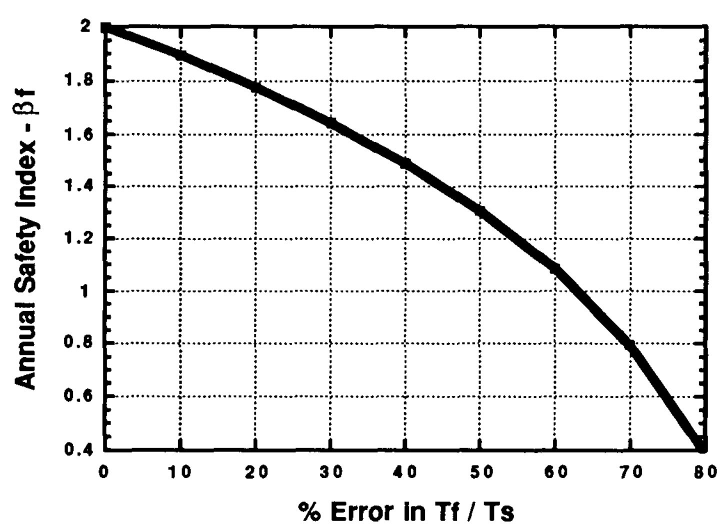

Figure 3.7 - Effects of overestimation errors in Tf / Ts

Load and Resistance Factor Effects

Premised upon Lognormally distributed loadings and capacities, the following expressions can be developed to define the loading and resistance factors required for a ship structure Load and Resistance Factor Design (LRFD) format:

$$\phi_{50}\, R_{50} \geq \gamma_{50}\, S_{50} \tag{3.14}$$

$$\phi_{50} = B_R \exp(-0.75\, \beta\, \sigma_{\ln R}) \tag{3.15}$$

$$\gamma_{50} = B_S \exp(0.75\, \beta\, \sigma_{\ln S}) \tag{3.16}$$

where ϕ_{50} is the median resistance factor (generally less than unity), γ_{50} is the median loading factor (generally greater than unity), B_R is the median resistance bias = true median capacity / nominal median capacity, and B_S is the median loading bias = true median loading / nominal median loading.

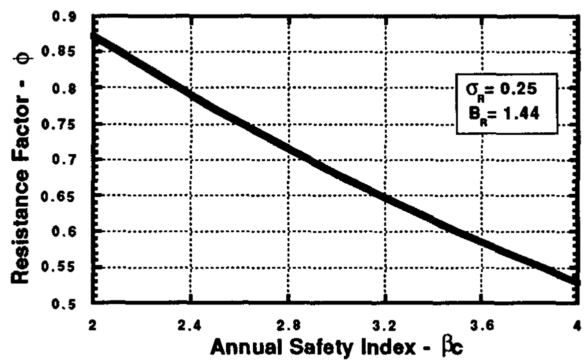

Figure 3.8 - Resistance factors

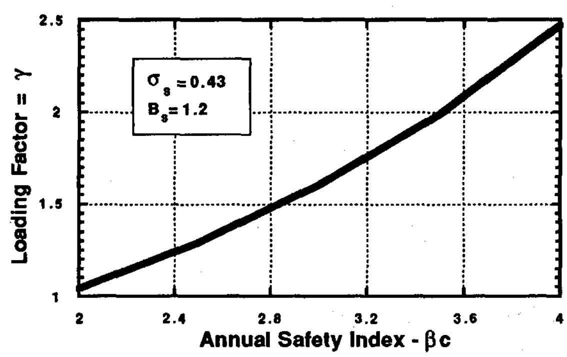

Figure 3.9 - Loading factors

Figures 3.8 and 3.9 illustrate the load and resistance factors for various capacity Safety Indices based on a capacity bias of B_R = 1.44 and a loading bias of B_S = 1.20. The capacity bias recognizes that the ship capacity will be determined using traditional linear elastic analyses based on the occurrence of first nominal yield in the ship structure system (1.15 factor for steel strength and 1.25 factor for maximum loading capacity above first yield). The loading bias recognizes the tendency for linear strip theory methods to under-estimate the stresses in extreme sea states.

For example, if it were desired to have a capacity Safety Index of $\beta c = 3.0$ ($Pf \approx 1$ E-3 per year), then the resistance factor $\phi \approx 0.7$ and the load factor $\gamma \approx 1.6$.

Figures 3.10 and 3.11 illustrate the effects of errors in the estimated loading and capacity uncertainties. Errors in the evaluation of median biases in the capacities and loadings have not been included. The errors in uncertainties have been illustrated for under-estimations that would result in the loading and resistance factors being too low; this would result in the ship structure being weaker than intended. A target Safety Index of βc = 3.0 has been assumed in this illustration.

A 50 % under-estimate of the uncertainties associated with the resistance factor results in a 30 % error in the resistance factor. A 50 % under-estimate in the uncertainties associated with the loading factor results in a 90 % error in the loading factor. It is much more important to monitor and control the potential for HOE in making evaluations of the uncertainties associated with the loadings

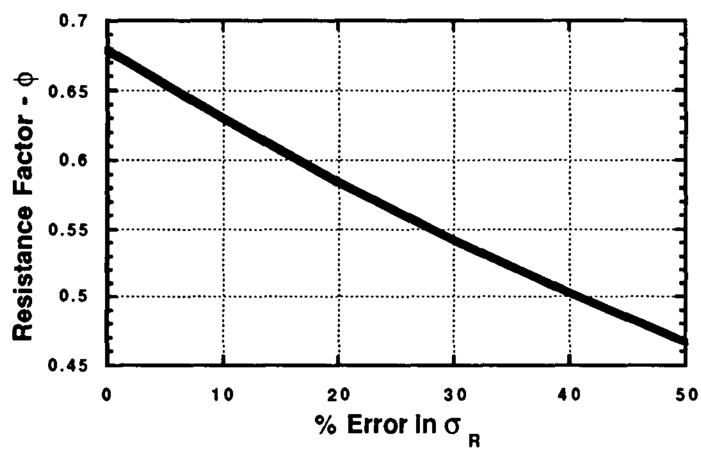

Figure 3.10 - Effects of errors in resistance uncertainties on LRFD resistance factor

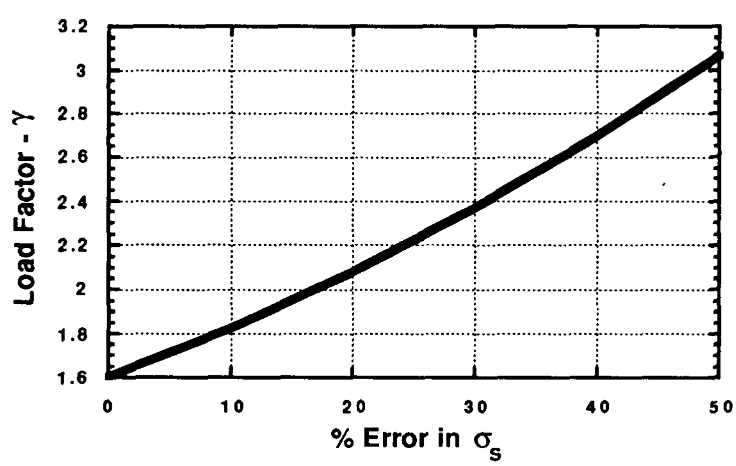

Figure 3.11 - Effects of errors in loading uncertainties on LRFD loading factor

Risk & Risk Management

Risk is defined in this report as the product of the likelihood that adequate or acceptable quality is not achieved and the consequences associated with the lack of achieved quality.

Risk results from uncertainties. Uncertainties result from inherent variabilities (aleatory), "professional" or "technical" sources (analytical, modeling, parameter, epistemic), and "human" sources (individuals, teams, organizations, societies). Some uncertainties are random (aleatory) and some are systematic (epistemic). Some uncertainties can be managed (information sensitive, epistemic) and some uncertainties can not be managed (information insensitive, aleatory). Some uncertainties are essentially "static" (unchanging in time) and others are essentially "dynamic." Some uncertainties can be identified and quantified and some uncertainties can not be identified and quantified.

Consequences result from unrealized expectations and unanticipated lack of sufficient quality. Consequences can be expressed in terms of their frequency, their severity, their impacts (on site and off site), and their predictability.

Consequences can be expressed in a variety of ways and with a variety of metrics. Monetary costs are one way to measure and express consequences. Time (schedule, availability), injuries to humans, and injuries to the environment are other ways to express and measure consequences.

Some consequences can be managed or controlled (hazard mitigation measures). Some consequences can not be managed or controlled. Some consequences can be evaluated objectively and quantitatively and some consequences can not be evaluated objectively and quantitatively.

Generally, there are significant uncertainties associated with the results of evaluations of consequences. This is particularly so as one projects the consequences of insufficient or unacceptable quality far into the future.

Evaluations of consequences are difficult to make and express. Evaluations of consequences are very susceptible to the values, views, and "biases" of the evaluators.

Some consequences are essentially "static." They do not change significantly in time. Other consequences are very "dynamic" in that they change markedly in time.

An identified risk is a management problem. A faulty or bad definition of a risk will breed additional risk and result in bad management of quality. A risk management framework is based on intelligent and perceptive risk identification, classification, analysis, evaluation, and response.

Risks have "sources", are translated to reality with "events", and are felt with "effects." There are initiating events (direct causes), contributing events (background causes), and compounding events (propagating or escalating causes). Risk management attempts to identify causes, detect potential and evolving events, and control effects.

Risks are independent and dependent. Risks can have partial dependence. If the occurrence of one risk does not influence the occurrence of another risk, then it is independent. If the magnitude of one risk is related to the magnitude of another risk then these two risks are correlated. Independence and correlation are critical issues in risk management.

Risks are controllable and uncontrollable. Controllable risks are those that are within the control of those that own, operate, design, classify, regulate, and build marine systems. Uncontrollable risks are those that are not within the control of the groups cited. Risk management is concerned primarily with controllable risks. Inherent risk and uncontrollable risk must be recognized and evaluated in the process of making decisions regarding the activities and ventures associated with marine systems.

A risk management system should be practical, realistic, and must be cost effective. Risk management need not be complicated nor require the collection of vast amounts of data, that in most cases of marine systems, does not exist. Excellent risk management is a combination of uncommon "common sense", qualified experience, judgment, knowledge, wisdom, intuition, and integrity. Mostly it is a willingness to operate in a caring and disciplined manner in approaching the critical features of any activity in which risk can be generated.

The purpose of a risk management system should be to enable and empower those that design, build, and operate marine systems. The purpose is to assist those groups to take the "right" risks and to achieve "acceptable" quality. *To try to eliminate risk is futile. To try to manage risks is the essence of man's activities in the sea.*

Risk analysis is the attempt to define and evaluate the sources, effects, and consequences of risks. Risk analysis can be qualitative and it can be quantitative. These are complimentary forms of risk analysis and they should be used to support each other.

Quantitative risk analysis can involve probability analysis, sensitivity analysis, scenario analysis, situation analysis, and correlation analysis. Quantitative risk analysis can be objective and / or subjective.

Qualitative risk analysis will involve the use of direct judgment, generally involves ranking and comparing attributes and options, and a descriptive analysis and evaluation.

Decisions

The purpose of developing qualitative and quantitative models of risks is to provide information for making good decisions regarding management of these risks. The development of a decision model to help solve problems is outlined in Figure 3.12.

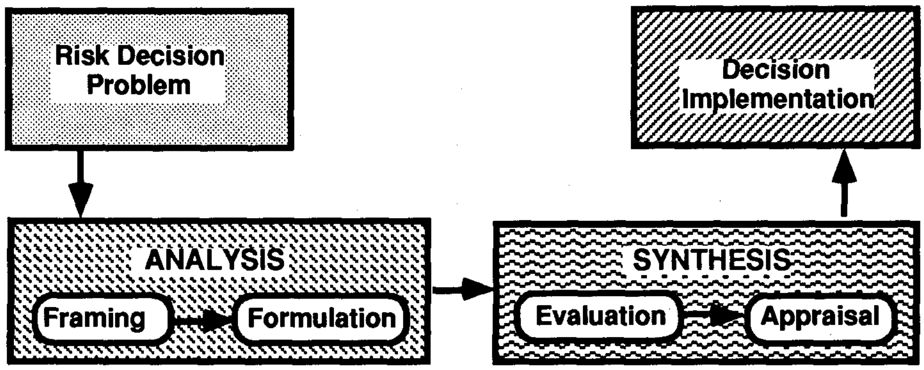

Figure 3.12 - Risk decision analysis

The decision analysis process is divided into two primary parts:

1) analysis, and
2) synthesis.

Analysis involves framing and formulation. These involve decomposition of the problem into its parts. The subsequent evaluation and appraisal involve synthesis in which the parts are combined into a whole to establish the attributes of each possible solution.

The purpose of framing is to avoid working the wrong problem. The purpose of framing is to state the precise nature of a problem and the objectives to be pursued.

Framing is structuring and re-stating the problem. One objective of framing is to surface the "unspoken agendas" that are generally present in a risk decision problem.

Formulation is a formal model based upon the problem. It is based on a decision process composed of three parts [Raffia, 1970]:

1) The alternatives available to the decision maker to achieve the particular goal.

2) The information that describes the relationship between the decisions and possible outcomes.

3) The preferences of the decision maker.

Information includes any form of model, forecast or probability assignment which indicates the possible outcome of the decision. Preferences express the values of the decision makers regarding the principal outcomes (e.g. which is more important, schedule or cost?).

A good decision is an action that is logically consistent with the alternatives available, the information available, and the preferences. Good decisions do not always result in good outcomes. Table 3.1 lists the attributes associated with good risk decision making processes [Flanagan, Norman, 1993]).

Table 3.1 - Attributes of good risk decision making processes

Framing	Surveys the full range of objectives to be fulfilled and the values implied by the choices
Alternatives	Thoroughly canvasses a wide range of alternative courses of action; possibility thinking
Information	Carefully weighs knowledge about the costs and risks of negative consequences as well as the positive consequences that could flow from each option. Intensely searches for new information relevant to further evaluation of the options. Keeps an open mind.
Evaluation	Correctly assimilates and takes account of any expert judgment and risk exposure, even when the judgment does not support the course of action initially preferred. Re-examines the positive and negative consequences of all known alternatives, including those originally regarded as unacceptable, before forming the final choice.
Implementa tion	Makes detailed provisions for implementing or executing the chosen course of action, with special attention to contingency plans that might be required if various known and unknown risks were to materialize.

Summary

Quality is freedom from unanticipated defects. Quality is fitness for purpose. Quality is meeting the requirements of those that own, operate, design, construct, and regulate marine structures. These requirements include those of serviceability, safety, compatibility, and durability.

Reliability is defined as the probability that a given level of quality will be achieved during the design, construction, and operating life-cycle phases of a marine structure. Reliability is the likelihood that the system will perform in an acceptable manner. Acceptable performance means that the system has desirable serviceability, safety, compatibility, and durability.

Reliability can be expressed as the probability that the demands placed on a marine structure can be supplied by that structure. The probability of failure or unreliability is the compliment of the reliability and is the likelihood of undesirable or unacceptable performance of a marine structure. Examples have been developed pertaining to the reliability characteristics associated with the capacity and durability of a marine structure that indicate the sensitivity of reliability to design and construction factors that affect loadings, strength, and the uncertainties associated with loadings and strength. Similar examples were developed to illustrate these effects on Loading and Resistance Factors.

Understanding these sensitivities allows one to direct QA / QC to the portions of the design process that have the highest probabilities of human errors and have the greatest effect on the reliability of the marine structure.

Risk represents the product of the likelihood of an event and the consequences associated with that event. Risks pervade all activities. Not all risks can be defined and quantified. A primary objective is to manage those risks that we can define and quantify and defend against those that we can not define and quantify.

Decisions involve framing and analysis. There are good decision making processes and the attributes of such processes have been defined. A good decision is an action that is logically consistent with the alternatives available, the information available, and the preferences. Good decisions do not always result in good outcomes.

The next chapter will examine aspects of QA / QC, their potential costs and benefits, and illustrate how one might develop evaluations of equitable balances in the costs of achieving quality and the benefits associated with that quality.

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Chapter 4

QUALITY ASSURANCE, CONTROL & COSTS

Quality Assurance & Control

Quality Assurance (QA) are those practices and procedures that are designed to help assure that an acceptable degree of quality is obtained. Quality assurance is focused on prevention of errors. Quality Control (QC) is associated with the implementation and verification of the QA practices and procedures. Quality control is intended to assure that the desired level of quality is actually achieved. Quality control is focused on reaction, identification of errors, rectification, and correction.

QA / QC measures are intended to assure that a desirable and acceptable reliability of the marine structure is achieved throughout its life [Bea, et al., 1994].

Quality is initiated with the conception of a service or product, defined with design, translated to reality with construction, and maintained with high quality operations.

Achieving quality goals is primarily dependent on people. QA / QC efforts are directed fundamentally at assuring that human and system performance is developed and maintained at acceptable levels. Experience has adequately demonstrated that most problems associated with inadequate quality in marine structures are associated with Human and Organization Errors (HOE). Such errors can occur in the concept development, design, construction, and operation life-cycle activities of a marine structure.

Figure 4.1 outlines the strategies that can be employed in defining QA / QC measures. These strategies include those put in place before the activity (prevention), during the activity (checking), after the activity (inspection), after the manufacture or construction (testing), and after the structure has been put in service (detection).

As will be discussed in the next section, the earlier QA / QC measures are able to detect the lack of acceptable quality, then the more effective can be the remediation.

Of all of the QA / QC measures, the most effective are those associated with prevention. As factors leading to lack of desirable quality are allowed to become more and more embedded in first the design, then the construction, and then the operation of a marine structure, then the more difficult they are to detect and correct. Personnel selection, training, and verification; the formation of cohesive teams and encouragement of teamwork, and the elimination of unnecessary complexity in procedures and structure - equipment systems are examples of effective QA / QC measures.

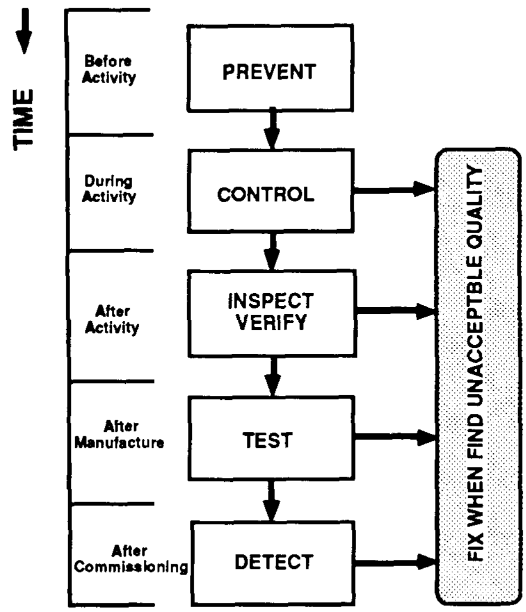

Figure 4.1 - Quality assurance and control strategies

Control QA / QC measures consist of procedures and activities that are implemented during design and construction activities to assure that desirable quality is achieved. Self-checking, checking by other team members, and verification by activity supervisors are examples of such activities.

Inspection and verification QA / QC measures consist of procedures and activities that are implemented after the design and construction activity or segment of that activity has been completed. Design documentation and construction production products are inspected to assure compliance with the applicable procedures and specifications. Verification of design assumptions and analyses and destructive and non-destructive testing of constructed elements are examples of such activities.

Detection QA / QC measures consist of procedures and activities that are implemented after the marine structure has been put in service to assure that desirable and acceptable quality are maintained. The use of shipboard monitoring systems and in-service inspections to assure that significant damage is not developing in the hull structure due to cracking and corrosion are examples of such activities.

Quality & Costs

Providing quality in the design, construction, and operation of a ship or offshore platform can result in lower life-cycle costs, be safer, and minimize unrealized expectations. Quality can result in significant benefits. But, quality costs.

Achieving an adequate level of quality is not quick, easy, or free. It can be costly in terms of the initial investments of manpower, time and other resources required to achieve it (Figure 4.2) . But, if it is developed and maintained, it can result in significant savings in future costs.

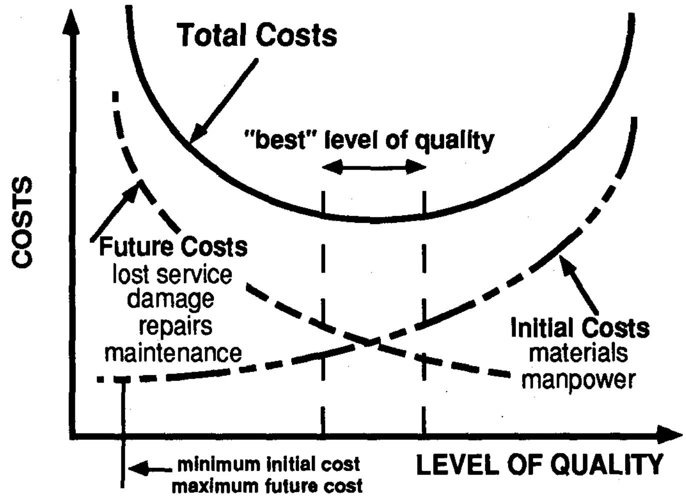

Figure 4.2 - Consideration of initial and future costs associated with various levels of quality

Consideration of future costs requires a long-term view of the performance characteristics of a system. The objective is to find the level or degree of quality that will minimize the total of initial and future costs.

Different levels of quality are needed for different levels of "criticality." If a structure element, component, or system is particularly critical to the quality of a structure, then even though it may have identical initial costs, it may have very different future costs (Figure 4.3).

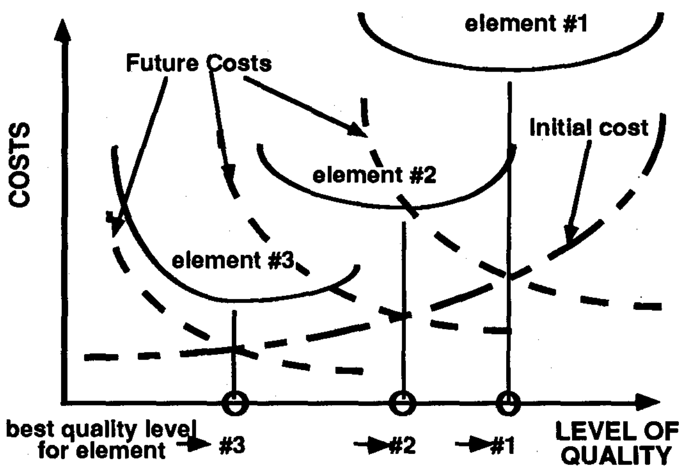

Figure 4.3 - Criticality should determine the level of quality

Higher levels of quality and more intense QA / QC measures should be relegated to those element, components, and systems that have higher levels of criticality.

The costs to correct insufficient quality (errors) are a function of when the deficiencies are detected and corrected (Figure 4.4). The earlier they are caught and fixed, then the less the costs. The most expensive time to fix quality errors is after the system is placed in service. This places a large premium on early detection and correction of errors. Not only are there are large direct future costs associated with fixing errors, but as well there are large indirect costs associated with loss of business and loss of image.

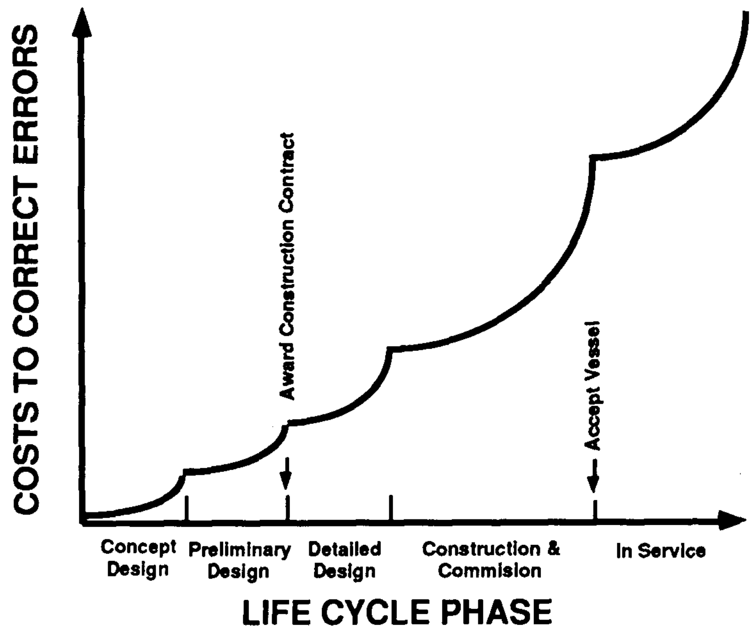

Figure 4.4 - Life cycle costs to correct errors

Assuming that the costs of quality varies linearly with the logarithm of the probability of insufficient quality, the "optimum" annual reliability that produces the lowest total of initial costs and future costs can be shown to be [Bea, 1992; Bea, 1994b]:

$$Ps = 1 - \frac{0.4348}{CR\, pvf} \tag{4.1}$$

where CR is a cost ratio and pvf is a present value discount function. The cost ratio is the ratio of the costs associated with not realizing the desired level of quality (CF) to the costs required to reduce the likelihood of not realizing the desired level of quality by a factor of ten (ΔC_i). For a continuous discount function and long-life structures (life $\geq$ 10 years), pvf $\approx r^{-1}$ where r is the monetary net discount rate (investment rate minus inflation rate). For short-life structures (life $\leq$ 5 years), pvf $\approx$ L, where L is the life in years.

As shown in Figure 4.5, as the costs associated with development of insufficient quality increases, the reliability must increase. As the initial costs to achieve quality increases, the optimum reliability decreases. The optimum reliability is based on the quality that will develop the lowest total initial and future costs. The marginal probability of insufficient quality is double the optimum quality probability. It is the quality in which the incremental investment to achieve quality equals the incremental future benefit (cost / benefit = 1.0). Reliability of a marine structure element, component, and system is a function of its criticality expressed by the product of the cost ratio and present value function.

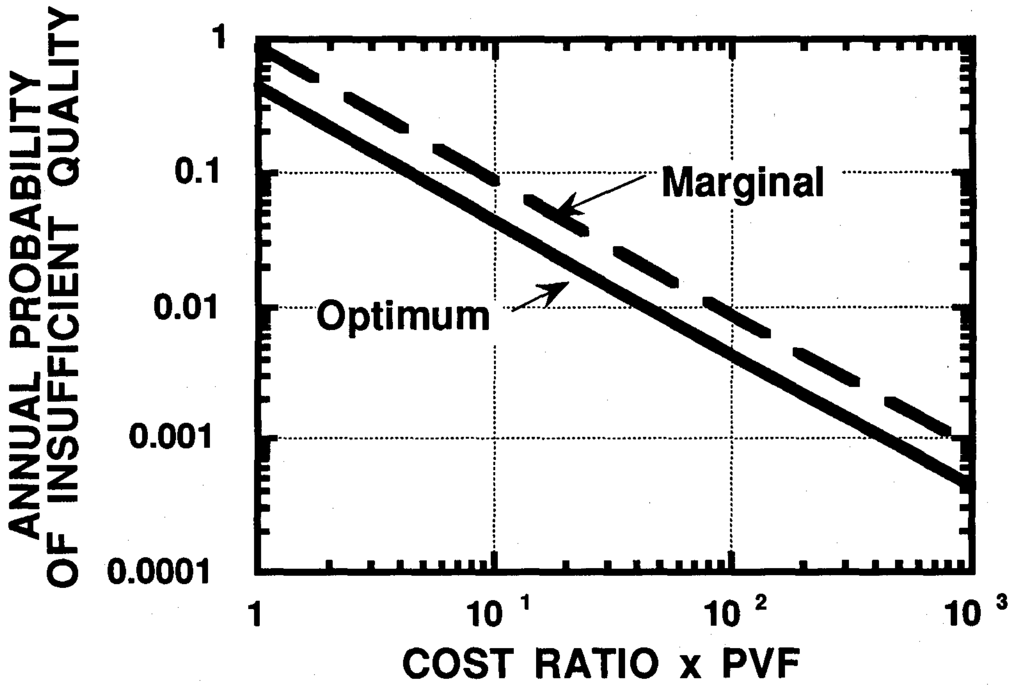

Figure 4.5 - The economics and likelihood of insufficient quality

Quality can be a substantial competitive aspect in industrial activities. If a purchaser or user recognizes the benefits of adequate quality and is able and willing to pay for it, then quality can be a competitive advantage. If a purchaser or user does not recognize the benefits of adequate quality or is unable or unwilling to pay for it, then quality can be a competitive disadvantage. Purchaser / owner quality goals must be carefully defined so that uniformity can be developed in the degrees of quality offered in a product or service sector. Once these goals have been defined, then the purchaser / owner must be willing to pay for the required quality.

It is important to recognize that the society being served by the industry also has a stake in quality. The industry must have adequate profitability to have adequate resources to invest in achieving adequate quality. The general public that is served by the marine industries must be willing to pay for the quality that it may demand [Bea, 1993].

Cost Based Durability

Cost & Code Based Calibration of LRFD

The choice of a Safety Index (i.e. probability of failure) to be used in development of design guidelines is a key issue. The following example addresses the development of design durability load and resistance factors based on two different approaches; one is based on the economics of durability and the other is based on calibration with existing classification guidelines.

For example, suppose for a given class of ships CF = \$ 500 million, ΔCi = \$25 million, and pvf = 10 (L = 20 years, net discount rate = 10 %), then based on the foregoing economics based quality developments, $\beta c = 2.9$ (Pfo = 2 E-3 per year). If however the ship owner argued that due to insurance and other "protective measures" that CF = \$100 million, then $\beta c = 2.3$ (Pfo = 1 E-2). A reliability philosophy that was "weighted" toward avoiding costs associated with failure and initial costs could result in increasing the likelihood of failure by a factor of 10. There would be important effects on the loading and resistance factors.

A second approach would be to "calibrate" the load and resistance factors to give the same results as a current "accepted" Working Stress Design (WSD) format guideline. Given a Working Stress Design (WSD) format, the median factor-of-safety, FS, can be expressed as follows:

$$R_{50} / FS_{50} \geq S_{50} \tag{4.2}$$

$$FS_{50} = R_{50} / S_{50} \tag{4.3}$$

$$FS_{50} = (B_S / B_R) \exp(\beta c \sigma) \tag{4.4}$$

$$FS_{50} = \gamma_{50} / \phi_{50} \tag{4.5}$$

Given the previous example in which $B_S = 1.20$, $B_R = 1.44$, $\beta c = 3.0$, and $\sigma = 0.5$, then $FS_{50} = 3.73$. Given that the design loadings were based on 100-year conditions:

$$FS_{99} = FS_{50} \exp -(2.33\, \sigma_S) \tag{4.6}$$

Thus, $FS_{99} = 1.36$. Given a load factor $\gamma_{50} = 1.2$, then based on a "correct" $\beta c = 3.0$, $\phi_{50} = 0.88$. If however, the present "accepted" design guideline implied $\beta c = 2.6$, then $FS_{50} = 3.06$ and $FS_{99} = 1.2$. Given a load factor $\gamma_{50} = 1.2$, then $\phi_{50} = 1.0$.

The use of a "calibration" approach would produce a significant "error" resulting in an under-estimate of the load factor. Calibration of LRFD factors to existing codes will give the "correct" answer only when the existing code has incorporated sufficient levels of reliability and durability. The bias and uncertainties associated with the loading and capacity factors must be correctly evaluated if there are to be reasonable proportioning of safety between the loading and resistance factors.

Examples of Cost Based Durability Criteria

An example application of these developments is illustrated in Figure 4.6 for Critical Structural Details (CSD) in a 250,000 DWT ULCC. The numbers of fatigue failures (through thickness fractures) that can be anticipated in a ship hull structure during 5 year periods throughout a service life of 20 years are shown. It was assumed that the ship hull structure had 10,000 CSD whose fatigue strength had been uniformly determined by β_D's ranging from 1.0 to 3.0 (σ assumed = 1.0).

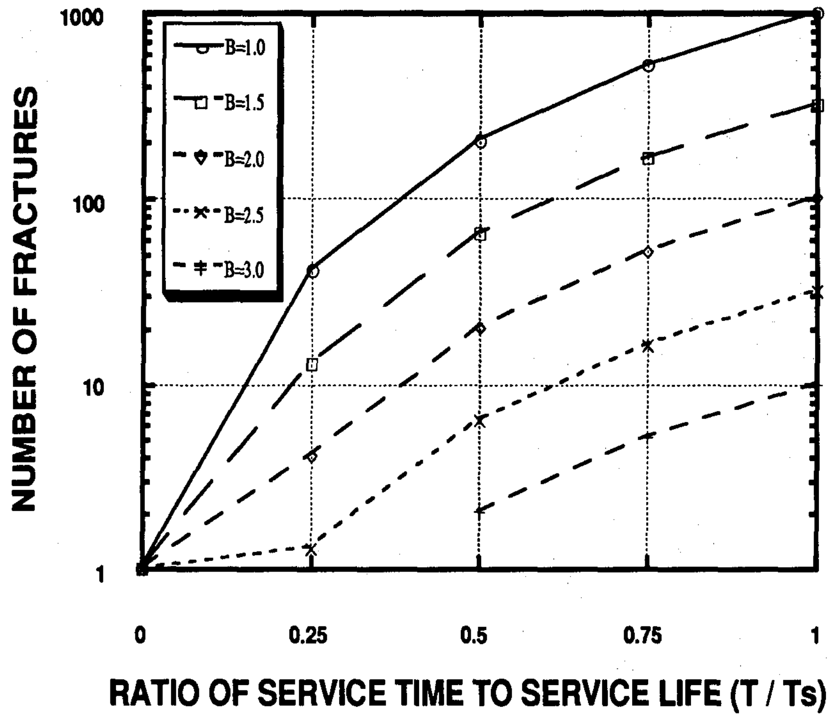

Figure 4.6 - Number of CSD fatigue failures in ULCC

The ship that had its CSD $\beta_D = 2.5$ had 6 fatigue failures during the first 10 years as compared with the ship that had its CSD $\beta_D = 1.0$ with 203 fatigue failures during the same time period. For fatigue design Safety Indices between 1 and 3, the number of fractures for a 20-year lifetime ranges from less than 20 to in excess of 1,000.

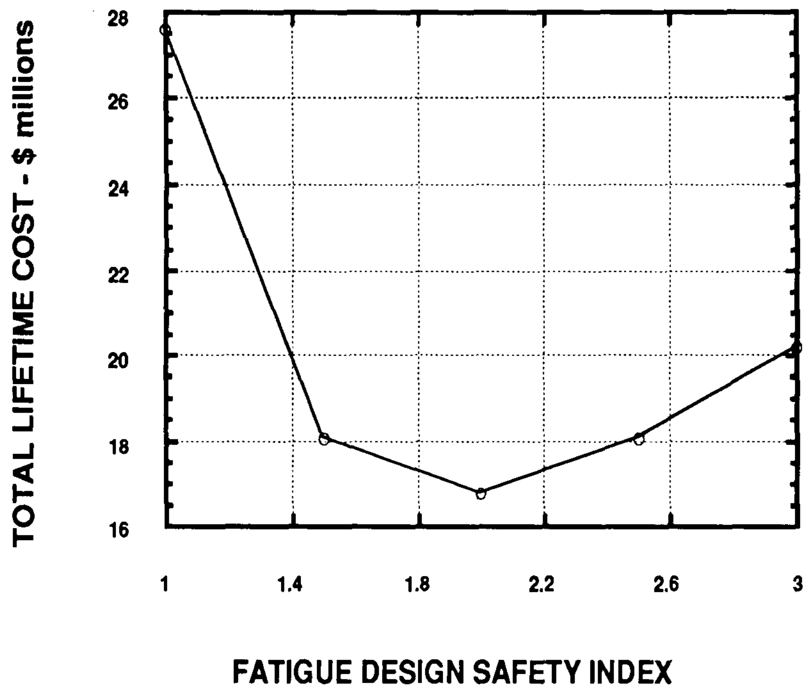

Figure 4.7 - Lifetime (20 year) costs in example ULCC hull structure as function of the fatigue design safety index

The foregoing information has been used to estimate the total life-cycle costs associated with fatigue fractures (Figure 4.7). It was assumed that the inspection process was capable of detecting the through-wall fractures that were developed at 5-year intervals, and that these fractures were immediately repaired to the initial condition (three IMR cycles). It was assumed that the initial cost differential between designing and constructing for a CSD $\beta_D = 1.0$ to CSD $\beta_D = 3.0$ cost $10 millions. Further, it was assumed that the total present valued cost associated with each fatigue fracture was $10,000 (this included inspection, repair, and out-of-service costs).

The results indicate a fatigue design Safety Index of about $\beta = 2.0$ is optimum. Lower and higher initial cost fatigue design Safety Index alternatives result in higher total costs.

Corrosion Durability Alternatives Cost Evaluation

A corrosion durability alternative evaluation can be developed in a manner similar to that for fatigue durability. It is assumed that the capacity of a CSD, Ru, can be expressed as:

$$Ru = S_f(ti - c) \tag{4.7}$$

Sf is the failure stress per unit width of the CSD, ti is the initial thickness of the CSD, and c is the corrosion wastage. Note that corrosion allowances such as are included in some classification rules would be incorporated in ti. The corrosion wastage can be expressed as:

$$c = Rc\,T \tag{4.8}$$

Rc is an average corrosion rate for a given period of time, CSD location, and protection, and T is the corrosion exposure time. For coated surfaces, T can be defined as the time associated with loss of effectiveness of the coating. For unprotected surfaces, T would be referenced to the time of initiating service of the CSD.

Let the corrosion or wastage limit, Lc, be expressed as:

$$Lc = \frac{c}{ti_{50}} = \frac{Rc\,T}{ti} \tag{4.9}$$

Expressing the likelihood of a corrosion caused failure, Pfc, as:

$$Pfc = P[ti - c \leq t_L] \tag{4.10}$$

t_L is the limiting plate thickness of the CSD. Assuming lognormally distributed corrosion and plate thickness variables, the corrosion Safety Index, βc, can be expressed as:

$$\beta c = \frac{\ln \dfrac{(to - Rc\,T)}{t_L}}{s_{\ln t}} \tag{4.11}$$

The change of the corrosion Safety Index as a function of time after the corrosion protection has lost its effectiveness can be expressed as:

$$\beta c(T) = \frac{\ln \left\{ \left(1 - \dfrac{Rc\,T}{to}\right) FS_{50i} \right\}}{s_{\ln t}} \tag{4.12}$$

The corrosion limit can be expressed as:

$$Lc = 1 - \frac{\exp(bc\, \sigma_{lnt})}{FS_{50i}} \tag{4.13}$$

σ_{lnt} is the uncertainty measure (standard deviation of the logarithms) associated with the corrosion rate, Rc, the time to corrosion protection breakdown, T, and the uncertainties associated with determination of the limiting plate thickness, t_L. FS_{50i} is the initial central factor of safety used in design of the CSD.

Very large variabilities are associated with corrosion rates of CSD in various parts of tanker hull structures. For example, the corrosion database developed and described in Bea [1993] indicate σ_{lnRc} = 0.5 to greater than 1.5.

For example, given a corrosion safety index of βc = 2.0 (about 1/100 chance of exceeding the prescribed limit in a given year), an uncertainty measure s_{lnt} = 1.0, and a central factor of safety of 10, the resulting corrosion limit would be Lc = 26 percent.

An understanding of the change in the corrosion Safety Index as a function of the corrosion exposure period is illustrated in Figure 4.8. This example has been based on an initial CSD plate thickness of 15 mm, average corrosion rates of Rc = 0.5 to 1.0 mm/year, a total uncertainty s_{lnt} = 1.0, and initial central factors of safety, FS, of 5 to 10. As the corrosion rate increases, the rate of increase of the probability of corrosion failure (exceeding a specified limit) in a given period increases. The initial factor of safety has no effect on the rate of change of the probability of failure as a function of corrosion exposure time.

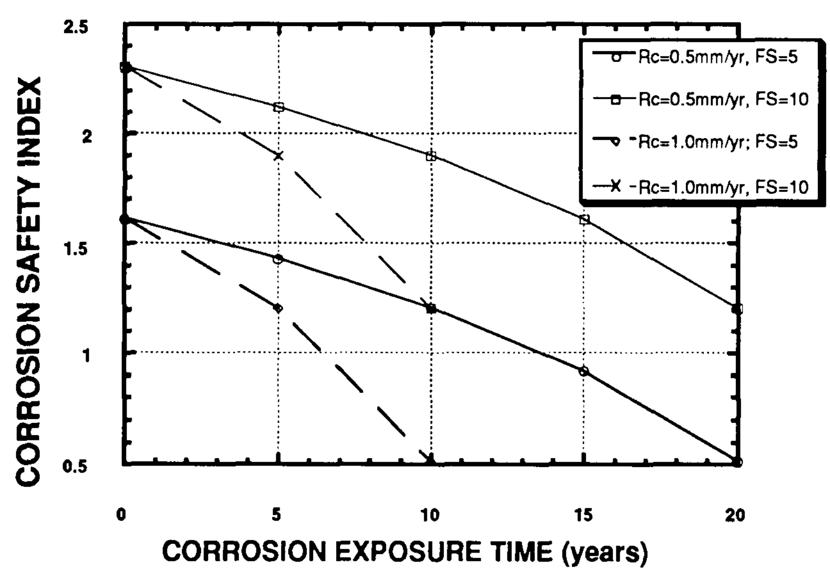

Figure 4.8 - Variation of corrosion Safety Index as function of the exposure time, average corrosion rate, and initial design central factors of safety

An example application of the foregoing can be developed as follows. Assume that ballast tank CSD have been designed in a double hull ULCC with an initial central factor of safety of 10. The initial thickness of the CSD is 15 mm. The expected (average) corrosion rate during exposure of the steel in these tanks is 0.5 mm/year. The total uncertainty associated with the corrosion effects is $s_{lnt} = 1.0$. The total surface area of the ballast tanks is 400,000 ft^2.

Three corrosion durability alternatives are being considered: 1) no initial protective coating and cathodic protection, 2) a 5-year expected life coating and cathodic protection system for all ballast tank surfaces, and 3) a 10-year expected life coating and cathodic protection system for all ballast tank surfaces. The corrosion limit has been defined so that the minimum corrosion Safety Index is 2.0; Lc = 25 percent wastage. Periodic surveys will be conducted to assure that this limit is detected.

It will be assumed that it costs \$10 ft^2 to provide the 5-year corrosion protection and \$15 ft^2 to provide the 10-year corrosion system when the ship is built. For the 5-year and 10-year protection systems, it will cost \$20 ft^2 and \$25 ft^2 present valued costs, respectively, when the protection must be renewed. The initial no protection system will be designed with a 10 percent corrosion allowance on the CSD that will cost \$4,000 per ton. The alternatives will be assessed for a 20-year life.

In the case of the no initial protective coating system, the corrosion limit will be expected to be exceeded in 10 years. At this time, a 10-year protection system will be installed. In the case of the initial 5-year protection system, the corrosion limit will be expected to be exceeded in 13 years. At this time, 10-year protection system will be installed. In the case of the initial 10-year protection system, the corrosion limit will be exceeded in 18 years. At this time, a 5-year protection will be installed.

The results of this example are summarized in Figure 4.9. The no initial protection system has the largest present valued cost. The 5-year and 10-year protection systems have a present valued total cost less than half of the initially unprotected system. There is little difference between the 5-year and 10-year protection systems.

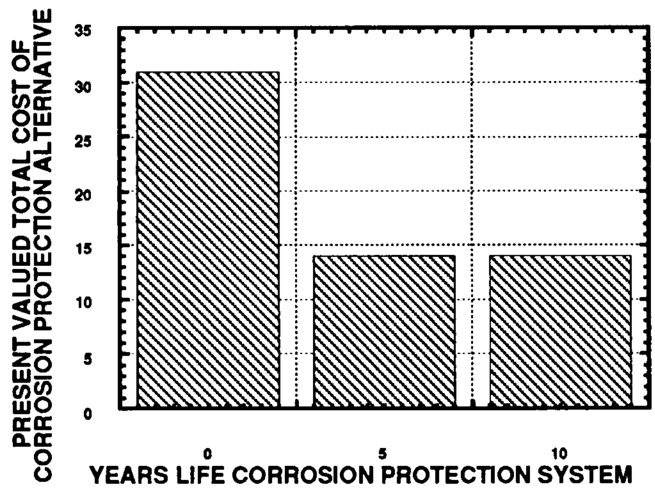

Figure 4.9 - Lifetime (20 year) costs associated with three alternative corrosion protection systems

Application

Suppose a ship owner is presented with three durability options for a new ULCC that is intended for 20 years of operation. Table 4.1 summarizes the initial costs (millions of U. S. dollars) associated with each of the options including the additional costs associated with heavier scantlings to increase the fatigue durability of CSD and corrosion protection in the ballast tanks. Option #1 is designed to minimum Class durability requirements (fatigue bf_D= 1.0 and no coatings in the ballast tanks) and Option #3 is designed to result in very high durability (fatigue bf_D= 3.0 and 10-year coatings in the ballast tanks).

Option #1 is the minimum initial cost ULCC and Option #3 is the highest initial cost ULCC. The initial cost of Option #3 is 17 % greater than the lowest initial cost option.

Table 4.1 - Economics based evaluation of fatigue and corrosion durability options

Option	Initial Cost $ MM	Initial Cost with coatings $ MM	Present Valued Fatigue Costs $ MM	Present Valued Corros. Costs $ MM	Present Valued Total Costs $ MM	% of Option #1
#1	95	95	23	31	149	100
#2	100	104	27	10	131	88
#3	105	111	15	10	136	91

Consideration of the lifetime durability costs indicates quite a different picture of the economics. Even though it initially cost $ 9 millions more than the minimum cost option, Option #2 results in the minimum total present valued lifetime cost. Over a 20-year operating period, the cost of Option #2 is 88 % of the minimum initial cost option. Even though designed and maintained to be the most durable option, Option #3 results in a higher lifetime present valued cost than Option #2. The initial cost investment in durability is not offset by the reduced future maintenance costs.

Summary

Quality Assurance (QA) are those practices and procedures that are designed to help assure that an acceptable degree of quality is obtained. Quality Control (QC) is associated with the implementation and verification of the QA practices and procedures. Quality control is intended to assure that the desired level of quality is actually achieved. QA / QC measures are intended to assure that a desirable and acceptable reliability of the marine structure is achieved throughout its life.

Given that quality goals have been defined, achieving these quality goals is primarily dependent on people. Thus, QA / QC efforts are directed fundamentally at assuring that human and system performance is developed and maintained at acceptable levels. Experience has adequately demonstrated that most problems associated with inadequate quality in marine structures are associated with Human and Organization Errors (HOE). Such errors can occur in the concept development, design, construction, and operation life-cycle activities of a marine structure.

Of all of the QA / QC measures, the most effective are those associated with prevention. As factors leading to lack of desirable quality are allowed to become more and more embedded in first the design, then the construction, and then the operation of a marine structure, then the more difficult they are to detect and correct. Personnel selection, training, and verification; the formation of cohesive teams and encouragement of teamwork, and the elimination of unnecessary complexity in procedures and structure - equipment systems are examples of effective QA / QC measures.

Providing quality in the design, construction, and operation of a ship or offshore platform can result in lower life-cycle costs, be safer, and minimize unrealized expectations. Quality can result in significant benefits. But, quality costs.

Quality can be a substantial competitive aspect in industrial activities. If a purchaser or user recognizes the benefits of adequate quality and is able and willing to pay for it, then quality can be a competitive advantage. If a purchaser or user does not recognize the benefits of adequate quality or is unable or unwilling to pay for it, then quality can be a competitive disadvantage.

Purchaser / owner quality goals must be carefully defined so that uniformity can be developed in the degrees of quality offered in a product or in a service sector. Once these goals have been defined, then the purchaser / owner must be willing to pay for the required quality. Ultimately, it is the public that is served that must pay the price for quality.

Chapter 5

HUMAN ERRORS: NON-MARINE STRUCTURES

Introduction

One of the primary tasks in this project was to review the literature on HOE in structure design and construction. This review included available background on the roles of HOE in design and construction of conventional buildings and foundations, bridges, dams, airframes, nuclear power plants, and offshore platforms. In addition, literature regarding HOE in medical practice and computer software development were reviewed.

The central theme that developed from these reviews was consistent. The single largest source of reliability problems associated with structures is HOE. Approximately 80 + % of the "failures" of such systems is due to compounded HOE. HOE occurs in all of the life-cycle phases including design, construction, and maintenance. In "passive" systems, where the majority of human activities that influence reliability are confined to the design and construction phases, the majority of HOE occurs in the design phase. In "active" systems, where human activities are present in all life-cycle phases including the long-term operating phase, the majority (approximately 80 %) of HOE occurs or is made evident during the operating phase. Lack of recognition of HOE is the fundamental reason for the disparities between computed or notional reliabilities and actuarial reliabilities.

Another important finding from this review regarded quantitative assessments of the causes of HOE related failures. The review did not identify one source of reliable objective data on HOE related design and construction failures. The studies have been sporadic and subjective in nature. There is no common classification or description of HOE in design and construction. There has been and still is no uniform classifications of errors or a uniform basis for identification of their causes and effects.

Congressional Committee Findings

In the early 1980's, there was a dramatic increase in failures of structures in the United States. This lead to a Congressional committee to investigate the failures and determine how they could be reduced. The findings of the committee included the following six factors to help prevent structural accidents [Committee on Science and Technology, 1983]:

1) improvements in the communications and organization in the construction industry.

2) improvements in the inspection of construction by the structural design engineer.

3) improvements in the general quality of the designs.

4) improvements in structural connection design details and shop drawings.

5) improvements in the selection of architects and engineers.

6) timely dissemination and application of technical data.

American Concrete Institute Survey

An extensive error survey was carried out in 1977 by the American Concrete Institute Committee into factors that influenced the failures of conventional concrete structures [Fraczek, 1979]. A questionnaire was prepared to define error detection, types of errors, consequences of errors, quality control, and the structural elements involved.

Tables 5.1 and 5.2 summarize the results from the survey in terms of the times and methods of error detection. Most of the errors that are developed during design are detected during construction and operations; few (less than 10 %) are detected during the design. This is in contrast with the errors that develop during construction, almost three-quarters of these errors are detected during the construction phase. The dominant mode of error detection is derived from observations of the structure itself (> 90 %); calculation and drawing checking is not very effective.

In terms of the time of detection of errors, these results have been confirmed in a recent survey of design and construction failures [Kaminsetzy, 1991] (Figure 5.1). Over half of the errors are detected during operations. Only 2 % of the errors are detected during the planning and design stages.

Table 5.1 - Time of detection of errors

Phase	Errors in Design %	Errors in Const. %
Design	8	--
Construction	42	75
Operation	50	25

Table 5.2 - Methods of error detection

Errors detected by	Errors in Design %	Errors in Const. %
Engineering	8	-
Construction	-	7
Operations	92	93

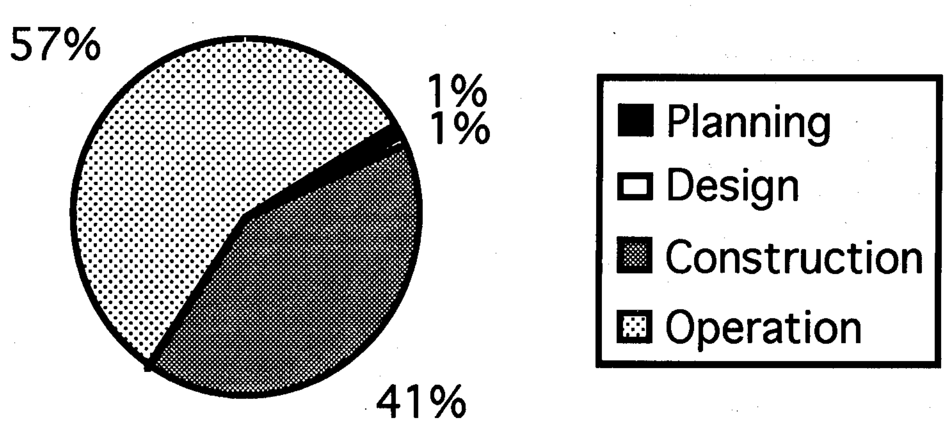

Figure 5.1 - Detection of errors in design and construction of concrete structures

European Building Failures Study

In a survey of European building failures [Hauser, 1979], the causes, sources, and detection possibilities were identified. This survey addressed conventional steel and concrete buildings. The results are summarized in Tables 5.3 and 5.4.

Insufficient knowledge and ignorance on the parts of the design engineer and contractor are responsible for the majority of failures. In terms of numbers of failures, the contractor is responsible for the majority of failures, however in terms of cost, the engineer is responsible for the majority of failures.

Hauser's survey and assessment indicates that the majority of errors could be detected with more effort expended in checking during the planning / concept development stage. A most important finding is that the majority of violations in planning, construction, or operation are intentional violations of general rules of procedure.

Table 5.3 - Causes of failure of conventional building structures

Causes	Errors in Design %	Errors in Const. %
insufficient knowledge	36	14
reliance on others	9	5
underestimated influences	16	11
error	13	4
negligence	14	54
unknown situations	7	3
other	5	9

Table 5.4 - Sources of errors in conventional building structures

Sources of Errors	number %	cost %
Engineering	28	41
Construction	33	17
Engineering & Constructor	11	20
Architect	8	1
Owner / user	5	13
Others	15	8

Hauser's conclusions regarding the sources of errors were confirmed by Kaminetzky [1991] (Figure 5.2). Kaminetsky also addressed conventional building structures. These results indicate that well over 50 % of the errors occur during the engineering phase of planning and design (total 58 %).

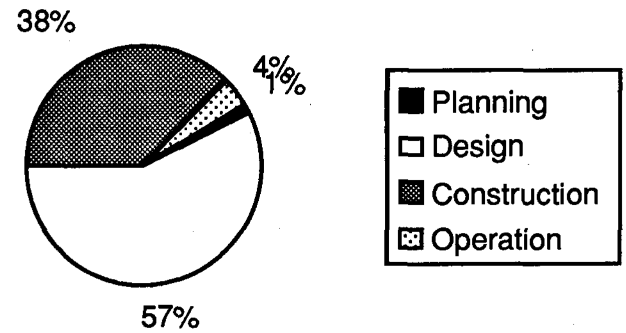

Figure 5.2 - Occurrences of errors in design and construction of structures

In a review of 212 cases in which engineering was responsible for the failure of structures (Figure 5.3), Matousek [1977] identified that insufficient knowledge was the single predominant cause (36 %). Note that negligence is a close second (27 %).

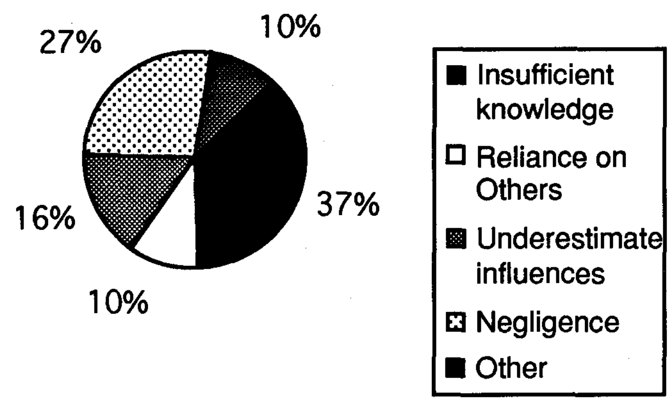

Figure 5.3 - Engineering causes of structure failures

In a similar review of 261 cases in which construction was responsible for the failure of conventional building structures (Figure 5.4), Matousek [1977] identified that negligence was the single predominant cause (58 %).

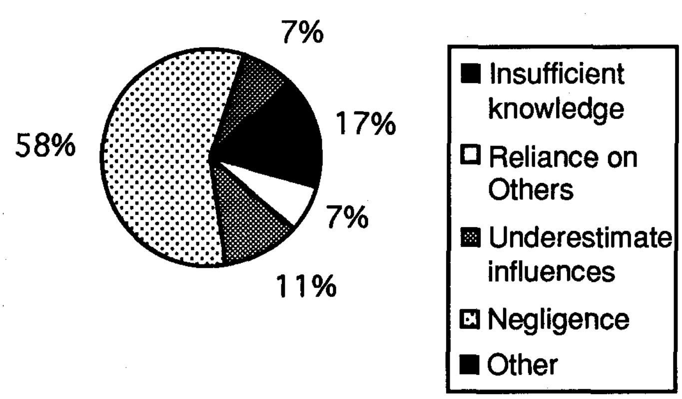

Figure 5.4 - Construction causes of structure failures

Hauser's conclusions regarding the causes of building structural failures were confirmed by Walker [1980] (Table 5.5). Engineering errors (loadings, structural behavior, calculations, instructions) are responsible for 54 % of the total number of causes of building structure failures. The majority of engineering errors (61 %) are due to errors in defining the loadings.

Table 5.5 - Primary causes of building structure failures

Cause	%
Ignorance of Loadings	33
Ignorance of structural behavior	10
Mistakes in calculations / drawings	7
Inadequate instructions / requirements	4
Ignoring instructions / requirements	9
Wrong fabrication / erection	13
Misuse, abuse	7
Random variations	10
Other	7

The European information developed by Matousek and Schneider [1977, 1979] was based on failure dossiers from insurance companies, published reports, and personal information from engineering firms and contractors. The following lists some of the primary conclusions from their study:

1) Most of the damage occurs during construction due to poorly planned construction factors (erection, assembly).

2) Errors in planning lead to a larger amount of structure and equipment damage while the consequences of errors in construction are more severe with respect to injuries.

3) The cause of failures is predominantly due to human errors; about 75 % of the instances of damage and 90 % of the costs of damage are due to human error.

4) About 45 % of failures are due to defects in design, 49 % due to construction, and 6 % due to improper use and inadequate maintenance.

5) A large proportion of the mistakes leading to failures could have been detected by adequate checking by the person next involved in the engineering and construction processes.

6) Most (32 %) of the mistakes could be detected by additional control; an additional 33 % and 17 % of the mistakes could be detected during the planning and construction stages, respectively.

7) Additional inspection and checking during planning, design, and construction is the most efficient method of error control.

Recent U. S. Structural & Construction Failures

Eldukair and Ayyub [1991] reviewed a total of 604 structural and construction failures in the U. S. during the period of 1975 - 1986. The survey was based on information gathered from the Engineering News Record (ENR) during this time period. ENR reported only on selected major failure cases and the failure causes that were studied were caused by variation within and departure from common engineering practices. Most of the failure cases were related to commercial buildings, bridge, and residential building projects.

The sources of error in the structure failures were mainly associated with technical errors. Seventy eight percent of the structural failures cases indicated that technical errors were the dominant source of error. Technical errors in design and construction were about equal contributors to the failures. Technical errors in operations had about half the incidence of those in design and construction.

Forty percent of the failures involved management errors (the total exceeds 100 % due to multiple causes or contributions to the failures). Management errors occurred primarily in work responsibilities (30 % of failures) and in communications (17 % of failures).

The distribution of failure cases with respect to the sources of error by participant are summarized in Table 5.6. The structure designer was involved in almost 50 % of the failures. The structure constructor was involved in almost 60 % of the failures.

Table 5.7 summarizes the distribution of failure causes relative to human behavior as defined by Eldukair and Ayyub [1991]. Insufficient knowledge, lack of proper training, underestimation of influence, and carelessness were dominant contributors to the failures.

Table 5.6 - Participants in structure errors

Participant	Failure Cases (%)
Project architect	3.0
Structural designer	48.2
Resident Engineer	31.1
Inspector	27.6
Contractor (staff)	3.8
Contractor	59.6
(workmen)	17.4
Operator	2.8

Table 5.7 - Failure Causes

Description of human behavior	Failure Cases (%)
Insufficient knowledge	66.7
Lack of training	57.3
Lack of foresight	33.0
Lack of authority	45.4
Reliance on others	29.0
Underestimation influ.	72.2
Negligence, carelessness	82.0
Unknown situation	33.3
Lack of communication	37.1

Table 5.8 summarizes the primary causes or initiating errors in the structure failures. In design, inadequate loading analyses and inadequate design of connections were both initiating causes in almost 50 % of the failures. Poor construction assembly procedures were present in more than 50 % of the failures.

Table 5.9 summarizes the secondary or contributing (or compounding) causes of structure failures. Environmental effects (bad weather) was present in 50 % of the failures. Lack of supervision, improper communication, and foreseeable deterioration were each present in about one-third of the failures.

Table 5.8 - Primary causes

Description	Failure Cases (%)
Inadequate loads	45.2
Inadequate connections	47.0
Reliance on construction accuracy	1.8
Errors in design calcs.	2.5
Unclear contracts	23.5
Contravention of instructions	21.8
Complexity of project system	1.2
Poor assembly proc.	54.3
Unforseeable	7.1
No information	15.5

Table 5.9 - Secondary causes

Description	Failure Cases (%)
Lack of engineering. responsibilities	8.1
Environmental effects	49.0
Poor mat. / equip. use	23.5
Lack of engineering specialization	0.9
Improper workmanship	7.0
Lack of safety training	1.7
Lack of work coord.	7.1
Lack of supervision	36.6
Improper communication	33.3
Application of new tech.	1.2
Forseeable deterioration	28.3
No information	34.0

Summary of Building Failures Studies

As a summary of building failures studies that were reviewed during this project, Table 5.10 summarizes the occurrence of errors that are developed in the life-cycle of conventional building structures by the particular cycle in which the error occurs. The column indicated as "other" includes cases where failure could not be attributed clearly to any one phase.

The results from the various surveys are reasonably consistent. The majority of the results indicate that a majority of errors occur in the design and construction phases with there being about an equal split between these two phases. The operating phase occurrence of errors is relatively low in most cases.

Table 5.10 - Summary of occurrence of errors in building structures

Reference	Design %	Construction %	Operation %	Other %
Matousek [1982]	45	49	8	2
Yamamoto, Ang [1982]	36	43	21	
Rackwitz, Hillemeir [1983]	46	30	23	1
Melchers, et al. [1983]	55	24	21	
Fraczek [1979]	51	49		
Allen [1979]	51	49		
Hadipriono [1985]	19	27	33	20
Hauser [1979]	37	35	5	23
Gonzales [1985]	29	59		12
Eldukair, Ayyub [1991]	51	57	31	4

Table 5.11 summarizes the identified causes of failures of conventional buildings derived from two studies. Again, the results from these two studies are reasonably consistent in their indications of the causes of errors. Insufficient knowledge is the primary cause followed by negligence and carelessness. Melchers [1983] notes that calculation blunders in design are only a minor source of error. These are usually detected and corrected in internal or self checking. The studies also indicate that preparation and interpretation of design drawings and contract documents are not a major source of error.

Table 5.11 - Causes of errors in design and construction of building structures

Reference	Negligence, carelessness %	Insufficient Knowledge %	Mistakes %	Reliance on others %	Other sources %
Matousek [1982]	35	38	9	6	12
Melchers, et al. [1983]	24	52	8	2	13
Eldukair, Ayyub [1991]	82	67		29	33 - 72

Fundamental misconceptions regarding, loadings, structural behavior and lack of attention to joint and supporting conditions appears to be the most serious source of design error [Melchers, 1983]. Often there are early warning signs or precursors for failures in either the design or construction processes, but often they are either not recognized or ignored [Melchers, 1983].

One might expect construction to be the dominant phase in which human errors occur. The results of the surveys do not bear this out. Separation of design and construction activities [Flint, Quinion, 1978], diffusion of responsibility in the construction process have created significant communication problems and resulted in many of the errors in construction [Flint, Quinion, 1978].

In a recently published study of buildings that failed during the Northridge California earthquake of 17 January 1994, Krawinkler [1994] observed that no recently completed building received a clean bill of health and he posed the question:

> *"Can we as engineers be satisfied with the state of knowledge available to practitioners with the level of protection implied by code design, and with the implementation process used in design and construction?"*

In reply, Krawinkler proposed that professional activities needed to be improved in five primary areas:

1) **Improved knowledge** - develop improved structural analysis and design procedures and develop socioeconomic models that tell engineers how to invest limited resources more effectively.

2) **Better quality control** - better understanding and interaction between owners, architects, engineers, and contractors.

3) **Better codes** - codes need to safeguard against weak links in the load paths to ensure a safe transfer of the maximum expected loads and there needs to be design verification recognizing inelastic behavior and incorporation of all elements that attract loads. Codes should provide criteria for damage control.
4) **Better code compliance** - violations of code requirements need to be stopped.

5) **Better education** - structural engineers need continuing education and equally as important education is needed for the public, owners and lenders, and other professionals.

These observations have direct applicability to design and construction of ship structures.

Errors in Structural Engineering

In his review of errors in structural engineering, Brown [1988] draws the following conclusions regarding classifications of errors:

1) Errors cannot be eliminated and only a small proportion can be identified prior to construction.

2) Engineers and contractors are responsible for most errors. Those of engineers result from omissions in professional preparation and experience of individuals, while those of contractors result from ignorance, neglect, and thoughtlessness.

3) Errors are largely evident as violations of accepted professional rules, codes, and paradigms.

4) Multiple errors are usually required to produce failures.

Brown [1988] draws the following conclusions regarding the causes of errors:

1) Poor training and pay of field inspectors.

2) Inadequate preparation and review of contract and shop drawings.

3) Breakdown or misinterpretation of communications between the design-construction-operation communities.

4) Lack of professional design and construction experience, especially when novel structures are needed.

5) Complexity of codes and specifications leading to misinterpretation and misapplication.

6) Unwarranted belief in calculations and specified extreme loads and properties.

7) Frequent personnel changes.

8) Compressed design - construction times.

Error Prone Structures

Pugsley [1973] studied the factors that background a large variety of failures of both conventional and innovative structures. As a result of this study, Pugsley advanced eight parameters of significance in promoting or causing failures:

1) The work involves new or unusual materials.

2) The construction methods are new or unusual.

3) The structural geometry or form are new or unusual.

4) The design and construction team is not experienced and well organized.

5) The engineers are not informed thorough an adequate research and development background.

6) The industrial - labor condition and climate are not stable.

7) The financial climate and work funding are not adequate.

8) The political climate is not benign.

Pugsley suggested that the intensity of the human error control measures should depend on the conditions surrounding the design and construction processes. Pugsley utilized the foregoing eight parameters to estimate a measure called the error proneness.

In his review of the Pugsley error proneness method, Allen [1984] contended that the method does not help in the detection and correction of errors. The difficulty was that the weights assigned to the eight factors before a failure by the people working on a project will differ greatly from those assigned by experts either during the project or after a failure.

Fox [1982] expanded Pugsley's idea to develop a numerical estimate of the failure probability from observable attributes of the structure. He listed the conditions that promote errors in design and construction as summarized in Table 5.12. Each of the eight design and construction conditions were given a rating from low to high with a numerical weight based on his evaluation of failures that had been promoted by each condition.

Table 5.12 - Calculation of gross error factor

Design Conditions	Low	Med. Low	Average	Med. High	High
• Thoroughness of preliminary investigations • Experience and ability of engineers • Familiarity of the engineers with the structure type and materials • Availability of time, money, and political assistance • Thoroughness of verification and checking • Relations between the engineers and contractors • Organization of the design team, communications, and responsibilities • Availability of design references and the simplicity of the structure					
Construction Conditions					
• Clarity, completeness and accuracy of specifications and drawings • Experience and ability of the contract • Familiarity of the contractor with the method of construction or the type of structure • Availability of time, money, equipment, or political assistance • Thoroughness of inspection, QA, QC • Relations between the engineer, owner, and contractor • Organization of the construction team • Labor relations (attitudes of the workers)					

Errors in Geotechnical Engineering

As a result of a review of more than 200 foundation failures, Sowers (1993) indicated that the majority of failures were due to either rejection of technology or ignorance (Figure 5.5); only 12 % of the failures were due to lack of technology.

The author found these results to be particularly interesting as they might apply to the design of ship structures. These two areas of engineering have much in common. In both areas the loadings are extremely difficult to determine accurately, the critical properties and performance characteristics of the system are difficult to determine and analyze accurately, the engineering procedures are complex and not easily reduced to design guidelines or codes, and both areas are subject to wide variety of organizational influences and pressures.

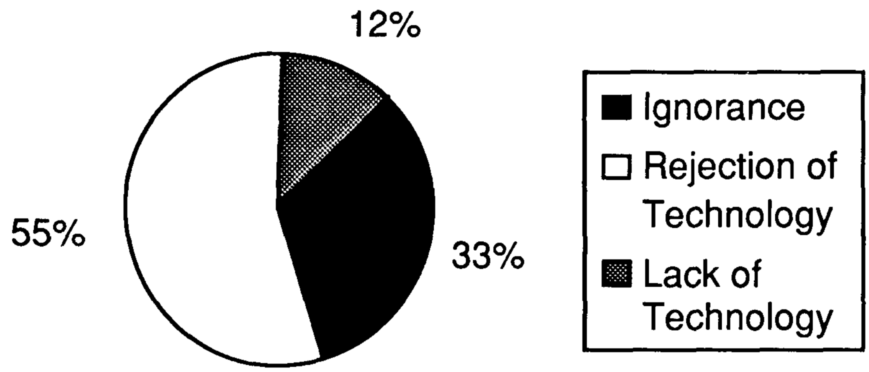

Figure 5.5 - Causes of foundation failures

Sowers suggests a number of approaches to reduce the 88 % of geotechnical failures that are due to ignorance and rejection of technology. He suggests continuing and intensifying:

> *"weeding out the ignorant and incompetent by better enforcement of engineering registration laws, increasing the awareness of engineers of their limitations in making decision involving both specialized and multi-disciplinary knowledge, and to add to the knowledge of practicing engineers through required continued education as technology develops."*

Sowers observes that reducing the proportion of failures caused by rejecting or failing to use current technology is very difficult. He then offers the follow comments about this problem:

> *"It essentially is faulty, absent, or malicious communication. Communication is a skill. It can be learned through education, both during the engineer's basic training and by continuing education. It must be developed by practice."*
>
> *"Balancing pressures is the most difficult challenge...The overall pressures of time, money, and the total environment effect each project in a different way. Sometimes they motivate those persons that apply pressure, sometimes they act in directly de motivating, distracting, or inhibiting the engineer. Of these, time and money are major influences on technology."*
>
> *"An innovative responsible engineer is the most important force in reducing failures. Our challenge in minimizing failures is instilling that sense of responsibility in engineering students and enhancing that responsibility among our professional colleagues."*

Control Approaches

There are two fundamental approaches to HOE problems in design and construction. The first is to limit the occurrence of HOE. The second is to reduce the impacts of HOE.

Essunger and Ostlund [1983] discuss two types of control; external and internal. External control was shown to have the advantage of being less dependent on such factors as the conditions of work, the working situation, and the economic result of the work. Internal control was shown to have the advantage of being executed by persons who often have a greater knowledge of the character of the work and who are aware of the kinds of problems that can be expected.

Essunger and Ostlund [1983] indicated that gross errors are relatively rare and it is generally not possible to discover them by a random check. Their work indicates that checking should be directed toward discovering errors which would lead to a failure which has severe consequences. They suggested that independent checking should be performed at key decision points in the project, especially where responsibility for the project changes hands.

The study by Hillemier [1982] indicates that the success of the realization of major projects depends more on the application of management rules than on exactly executed technical details. His work resulted in the following recommendations:

1) Information on damage and failure statistics should be developed and distributed to promote a better understanding of problems.

2) Basic decisions on the type of the structural systems are fundamentally made in the preliminary design stage; experience shows that errors established at the initial stage are hardly ever corrected later.

3) Activities affecting quality should be performed within an organization structure which has clearly defined responsibilities and authorities. It is critical to minimize information obstacles.

4) Ensuring the quality in engineering first requires an identification of critical areas in planning and execution, followed by the specification of priorities for their treatment.

5) Designers should be taught to think not only in terms of design limit states and load combinations, but also in terms of hazard or failure scenarios.

Lind [1986] suggested that education, personnel selection, task complexity reduction, quality control procedures, and the legal framework are all important in reducing human error, but not all are equally effective. Lind concluded that there is virtually no objective data on the effectiveness of human error control measures.

Nowak and Lind [1985] indicated that effective control of human errors requires a knowledge of the state of the system and a practical contingency plan of action for each state. They proposed an event tree model to represent the anticipated performance of structures during design, construction, and operations. A scenario was defined as a path in the event tree leading from the initial to the final state. They contended that the designer should consider all scenarios that end in failure of the structure, and by suitable design, should adjust the probabilities so that the probability of failure is acceptable. Nowak and Lind concluded that structures and their components can be placed into categories with regard to proneness to errors and sensitivity to errors. The control measures were directed to the components and steps in the design process that had the greatest effects on the likelihood of failure.

Nessim [1983] applied the decision tree approach to the problem of human error control. Nessim concluded that the optimal course of action is that which gives the maximum expected utility. This approach requires that each system be treated as a unique system and studied in great detail.

Nowak and Lind [1985] suggested the following procedure to identify where and how to place human error controls:

1) Develop the structural model, identify the parameters and limit state functions, estimate the distribution functions of the parameters.

2) Generate possible scenarios of departure from the developed model.

3) Calculate the reliability for each scenario.

4) Calculate the overall system reliability, including human errors and the expected value of the reliability for various scenarios with the correlation's.

5) Identify the most sensitive parts of the structure and the design process, concentrate control efforts on the items that have a significant effect on the overall reliability.

Nowak and Carr [1985] concluded that sensitivity functions and estimates of the frequencies for the corresponding errors can be used as criteria for selecting error control measures. This fits the control procedures to the important problems thus producing more efficient control. The objective is to design control systems to limit those errors which are the most consequential.

Checking Models in Structural Design

During the period 1982 through 1987, Melchers and Stewart conducted a series of studies that addressed the efficiency of checking models in structural design. Their studies addressed checking performed on three "levels": (1) self-checking, (2) independent detailed design checking, and (3) overview checking.

Their studies were based on questionnaires that were completed by conventional building design firms in Australia. Their studies were designed primarily to address errors of commission. Errors of commission were those that involved errors in the performance of design tasks including evaluation of design loadings and sizing structural members.

Errors of omission involving a failure to perform a task were shown to be substantially more difficult to catch and correct than errors of commission; the checking efficiency was more than an order of magnitude lower for errors of omission.

Regarding self-checking, their studies showed that self-checking detects only the small or minor errors that occur in calculations. Self-checking was not effective in catching errors due to misconceptions, oversights, or misunderstandings. The results of deliberate and conscious design decisions, once taken, appear seldom to be doubted by the designer or design team. The survey demonstrated that the detection rate for self-checking for small, or minor, initial error magnitudes is much greater than for larger initial error magnitudes. Quoting from their study conclusions:

> *"It might be concluded that (as a group) designers tend to be more concerned with relatively minor details and technicalities and that they tend to ignore larger errors....the present results appear to contradict conventional wisdom, it being commonly assumed that larger errors are more detectable."*

Their study developed some interesting data regarding the likelihood of calculation errors given a sequence of calculations. The data indicates that the larger the number of steps involved in the calculations, then the more likely is an error (Figure 5.6). Data were also developed regarding the likelihood of errors for different types of design tasks. These are summarized in Table 5.13.

In their study of the effectiveness of independent detailed design checking, two factors influencing checking effectiveness were isolated as being of particular interest. These were total time for checking (and therefore checking effort) and error magnitude. The errors included in the survey included calculations, table look-up, transfer of information, code look-up, and loading directions.

Regarding checking time, their work indicated that an S-shaped learning curve was appropriate (efficiency of checking versus time). The initial growth was attributed to the designer attempting to understand the design concept and procedure. This was followed by a period involving checking of each micro-task for any errors, and in which many of the errors were detected. Finally, the designer would reach the stage of diminishing returns, resulting in a reduced rate of checking efficiency. The S-shaped learning curve would be different for different types of design tasks and errors.

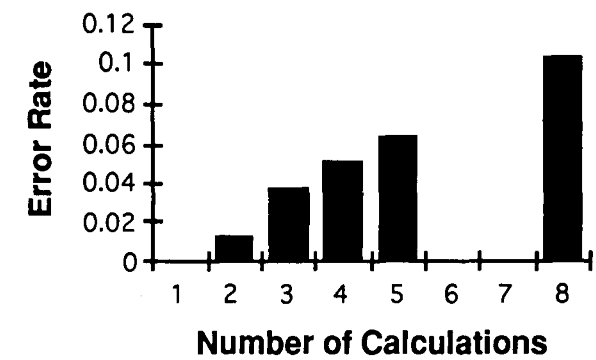

Figure 5.6 - The rates of errors based on a sequence of design calculations

In general, as checking time increased, the probability of detection of the errors increased. For the particular design tasks evaluated, at a checking time of 30 to 40 minutes, the checking efficiency increased to approximately 80 %.

Table 5.13
Design activity error rates

Error	Rate
Code interpretations	0.0150
Rankings	0.0135
Table look-ups	0.0126
Loading coefficients	0.1333
Loading directions	0.1000
Loading reduction factors	0.8000
Loading combinations	0.4167

Regarding error magnitude, the results indicated that larger errors were more easily detected than smaller ones. At an error magnitude of 200 %, the checking efficiency (probability of detection) was in the range of 60 % to 80 %.

In their study of overview checking, some 105 practicing engineers were surveyed. Decisions as to the adequacy of 11 simple structural designs, all simply supported beam members, each with a different loading configuration, were

evaluated. Based on the results, the probability of predicting whether a member design is safe is not a function of experience. The results indicated that if a proposed member design is deemed safe, then experienced engineers tend to be more efficient in assessing whether the member is oversized or not.

The relationship between an engineer's experience and the safety of a designed member is of particular interest. It has been shown by Walker [1980] that lack of experience is a major contributing cause in actual cases of structural failures. However, an analysis of structural failures by Blockley [1977] shows that while the designer's experience is a factor, its relative importance when compared with other causes of failure is very low. The study by Ingles and Nawar [1983] showed that engineers place great weight on experience for error reduction. The results of the work by Melchers, et al. [1989] indicate that such a perception may be false.

Nuclear Power Plants

A Probabilistic Risk Analysis (PRA) approach to the evaluation of nuclear power plants has been developed by Swain and Guttmann (1983) for the Nuclear Regulatory Commission (NRC). This approach was developed over about a 10 year period. It continues to be further detailed and developed [Luckas, et al., 1993; Barriere, et al., 1993].

The method developed by Swain and Guttman was identified as THERP (Technique for Human Error Rate Prediction). The THERP procedure included the following steps:

1) Define the system failure of interest, then determine the system functions that may be influenced by human errors and for which error probabilities are to be estimated.
2) List and analyze the human related operations.
3) Estimate the relevant error probabilities.
4) Estimate the effect of human errors on the system failure events.
5) Recommend changes in the system and recalculate the system failure probabilities.

The PRA is conducted using Event Trees. This approach will be further discussed and detailed in Chapter 8. The probability of failure at the end of each limb of the tree is the product of the conditional probabilities of all events in the path. The system probability of failure is obtained by summing the probabilities of the failure paths.

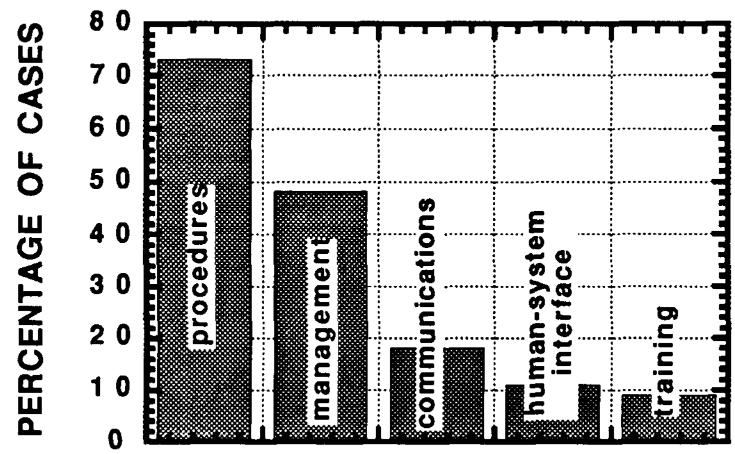

Figure 5.7 - Causes of accidents in nuclear power plants

Since 1979, and the Three Mile Island (TMI) power plant accident, the Nuclear Regulatory Commission (NRC) has embarked on an intense effort directed toward improved management of HOE in nuclear power plant operations. Figure 5.7 summarizes the results from 450 accident investigations that involved HOE in plant operations [Lucas, et al., 1993]. The total percentages sum to greater than 100 % because there can be multiple reasons for a given accident.

The data indicates that in about three-fourths of the cases, not following procedures is responsible for the accidents. Improper management is involved in about 50 % of the cases. The lack of proper training is involved less than 10 % of the time.

Data have been published recently on License Event Reports (LER) in operations of nuclear power plants [Luckas, et al, 1993]. Thirty two high consequence events were studied. Human error was responsible for 63 % of the severe events. The majority of the human errors were due to mistakes where the intention was erroneous and was purposefully executed (67 %).

The major source of the mistakes were the use of inadequate procedures (54 %). The event data indicate that procedures are frequently deficient, either in providing inadequate guidance or in omitting instructions for unexpected contingencies while performing operations. Errors of commission were responsible for 77 % of the events. These generally were the result of a procedural inadequacy and inadequate training.

The principal results from this study were that:

- Most events involve multiple influences.
- Most frequently cited human reliability influences are procedures and ergonomics.

- The majority of deficiencies are symptomatic of poor planing and preparation and concurrent deficiencies in training, communications, and organizational factors.
- The combinations of influences appear to be very sensitive to the context of the operating conditions.
- Recovery form the events (near-misses) is frequently aided by situation appropriate procedures, specific training, and the technical knowledge of the operations personnel.

Automotive Industry

In the automotive industry, Failure Mode and Effect Analysis (FEMA) methods have been applied (Ford Motor Company, 1972). The following steps have been integrated into these analyses:

1) Describe the failure mode,

2) Describe the effects of the failure,

3) Describe the causes of the failure,

4) Estimate the frequency of occurrence of the failure,

5) Estimate the severity of the failure,

6) Estimate the ability to detect and correct the failure,

7) Calculate the risk mitigation priority, and

8) Recommend corrective action.

The process is repeated for all potentially important failure modes. The risk mitigation priority is based on the relative magnitudes of the calculated risks. Human errors are implicitly accounted for in parts (4) and (6) in the process.

Aerospace Engineering

Consideration of human factors has been an integral part of development of structural systems for aircraft, including design, construction, and operating life-cycle phases of the aircraft [Bea, 1992]. Because of its importance, particular attention has and continues to be devoted to the in flight human error aspects [Hawkins, 1987]. Rabideau [1962] identified a Personnel Subsystem (PSS) reliability evaluation process that can be summarized as follows:

1) Analyze human functions as follows:

   a) identify and describe required human outputs (types, effects of environmental factors, and output tolerance limits),

   b) identify and describe response alternatives, initiating and coordination decisions, and valuations of feedback data,

   c) identify and describe required human inputs, and

   d) determine essential functional time aspects.

2) Identify potential sources of errors.

3) Estimate the probabilities of errors.

4) Rate the criticality of error effects by identifying the effects which potential error can exert on the system and by estimating the relative criticality of each effect.

5) Analyze trade-off factors including:

   a) possibilities of alternative functional and physical configurations,

   b) comparing alternatives in terms of the effects of human functional element's error potential, effects of implementation upon other functional / physical aspects, and implementation considerations relative to cost and schedule,

6) Test the functional and physical configurations.

7) Implement, monitor, record, and update the evaluations.

Hawkins [1987] proposed the SHEL conceptual model of human factors. The SHEL concept addresses Software, Hardware, Environment, and Liveware. Liveware refers to the humans that are at the center of the functional model. The engineering aspects of the Liveware include the physical size and shape, the fuel requirements (oxygen, food, water), input characteristics, information processing, output characteristics, and environmental tolerances. The remainder of the SHEL components are attached to this central component.

The Hardware or L-H interface is the one most commonly addressed and includes the field of "ergonomics" or man - machine compatibility. The Software or L-S interface includes the non-physical aspects of the system such as procedures, manual and checklist layout, symbology, and computer programs. Errors can develop within a given component such as an error in the Software and at the interface of the component with the Liveware such as an error in reading or interpreting the instructions in a manual of practice.

The Liveware-Environment of L-E interface is the one in which the external and internal environment has an effect on the Liveware. Cold, heat, vibration, motions, light, and other similar factors influence the error producing potential of the Liveware.

The last component is referred to as Liveware-Liveware. This indicates the interface between the individual and the organizations that influence the individual. The L-L interface is concerned with things such as leadership, cooperation, personality interactions, and other similar factors.

There can also be interfaces between any of the components. The H-E interface in the presence of severe environmental conditions can produce problems in the hardware, and so forth.

Bouton [1974] developed and applied an error disclosure process to the fatigue design of aerospace structures. Bouton contended that:

> *"Human error is the major problem with fatigue design due to the creation of defects and flaws during the fabrication, assembly, and operations processes. Because of the large uncertainties associated with fatigue design and because of the human error considerations, "fail-safe" design procedures must be adopted for airframe design."*

Medical

During this review, the author reviewed results from one current study being conducted by the medical profession on human factors as they relate to performance of radiation therapy [Henriksen, et al., 1993].

Sectors of the medical profession apparently have been working on problems of human factors for several decades primarily as applied to interfacing humans with machines and facilities. The field of "ergonomics" has had one of its primary development pushes from the needs of the medical profession.

The study reported by Henriksen, et al. [1993] was based on long-term site visits to hospitals and other treatment facilities, investigations of "incident" reports, and interviews with physicians, nurses, and patients. A team comprised of human factors specialists, assisted by a panel of physicians conducted the study.

A function and task analysis was performed to guide the evaluations in the areas of human-system interfaces, procedures, training and qualifications, and organizational polices and practices.

The framework for organization and analysis of the findings is shown in Figure 5.8. This figure shows the major contributing factors and individual factors in each of the major categories that are likely to influence the occurrence of

a "misadministrations" (human error). A precise definition was given to "misadminstrations" that involved both the occurrence and effects of errors.

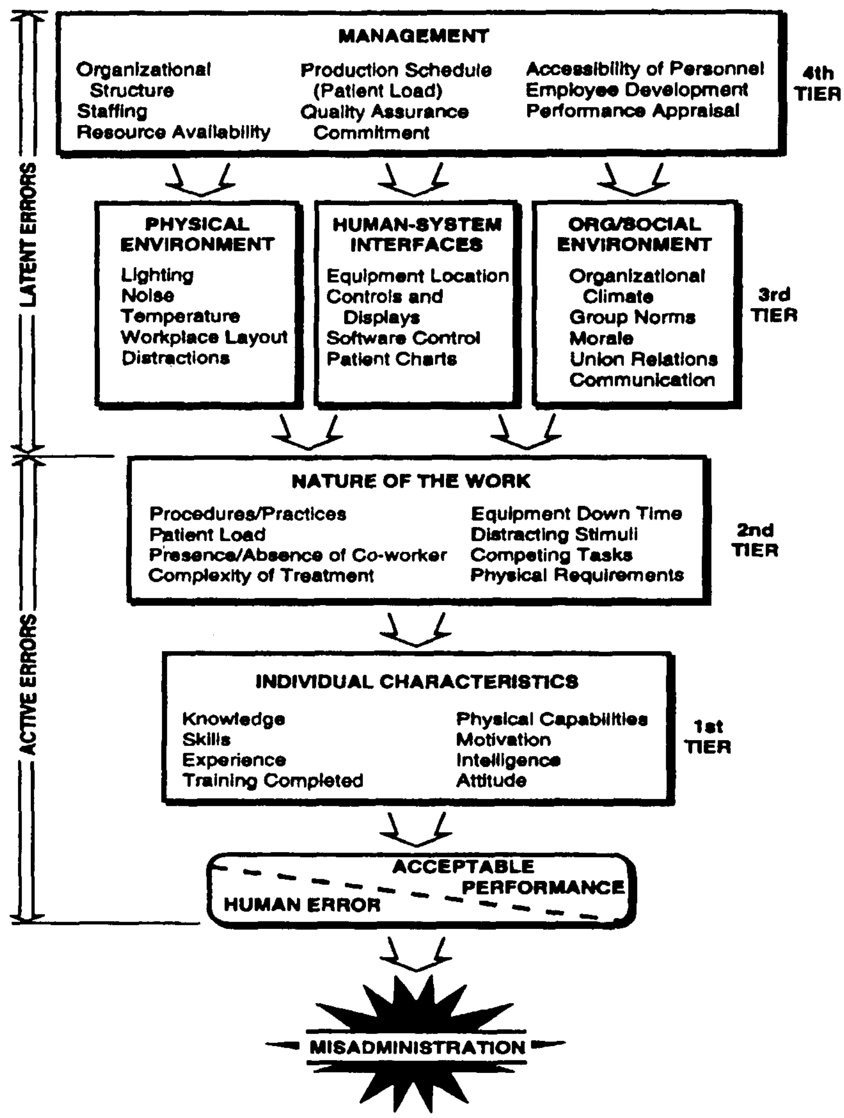

Figure 5.8 - Causative and contributing factors to human error in radiation therapy

The lowermost block in the figure shows a variable relationship between acceptable human performance and human error. The successive tiers of contributing factors in Figure 5.8 are arranged in a progressive manner with each successive tier having a direct influence on the factors of the preceding tier.

The first two tiers labeled "individual characteristics" and "nature of the work" reflect the individual qualities of technologists and the nature of their immediate work environment. Errors that can be traced to factors in the first two tiers are called active errors. Their occurrence is associated with the

delivery of treatment and they are frequently discovered immediately or in the near term.

In tiers 3 and 4 in Figure 5.8 are the broader scale workplace environment and managerial factors. Errors that can be traced to these tiers are propagated by those in decision making positions. The adverse consequences of latent errors in these two tiers may inert for some time in the overall system, only to breach the system defenses when they combine with other factors in unanticipated ways.

In the conclusions drawn from this study, the authors noted the following:

"A systems perspective leads one to suspect that the difficult to recognize latent errors that are made upstream by system designers and organizational policy makers permeate the system and contribute to the downstream active errors made by technologists."

The results of the study were reduced to a series of tables that addressed each of the blocks identified in Figure 5.8, identifying potential problem areas and implications for improvements. Major emphasis in the study was devoted to organizational and management factors.

Human Intervention

Human intervention is responsible for "near misses." Experience indicates that there are generally many more near misses than there are major accidents. Humans intervene to interrupt potentially catastrophic combinations of actions and events to bring systems back to within the safe operating zone.

Studies by Melchers (1990) have indicated that there are seven major factors involved in human interventions:

1. Education (information on how can things can and do go wrong)

2. Work environment that encourages open-minded, responsibility, integrity, and quality production

3. Reduction in complexity; simplification of complex tasks and systems; elegant simplicity

4. Personnel selection that emphasizes the necessary skills, capabilities, experience, commitments, and integrity

5. Self-checking in which the checking involves alternative procedures (independent)

6. External checking and inspection, particularly of the assumptions and precepts on which an activity or system is founded

7. Legal sanctions to deter negligence and deliberate malpractice.

Other Thoughts

From "Structural Failures Due to Human Error - What Research to Do ?" by D. E. Allen [1984]:

"Most design errors resulting in structural failure other than deterioration are due to misconception or lack of consideration of structural behavior, especially of the details, and of the kinds of loads and influences that occur."

"Most construction errors resulting in structural failure are due to incorrect procedures such as improper bracing, omissions, misplacements, wrong products and overloading."

"More systematic measures to avoid failure due to human error are therefore required. Such measures include checking, inspection, communication, proper organization of a project, etc., and come under the general heading of quality assurance."
From "Modeling Human Errors in Design" by A. Nowak [1991]:

"Human errors are the major cause of structural failure. Reliability depends to a large degree on the control of errors caused and consequences. Sensitivity analysis is an efficient method to identify the consequential errors. Then, special control efforts can be allocated in the most efficient way."

From "How Engineers Lose Touch" by E. S. Ferguson [1993]:

"Despite all the care engineers exercise and all their systems for ensuring correct engineering choices, evidence of faulty judgment shows up again and again in some of the most expensive and most carefully designed and tested machines of the twentieth century."

"Engineers need to be continually reminded that nearly all engineering failures result from faulty judgments rather than faulty calculations."

"Engineering students have been taught to rely far too completely on computer models, and their lack of old-fashioned, direct hands-on experience can be disastrous."

From "Launching the Space Shuttle Challenger: Disciplinary Deficiencies in the Analysis of Engineering Data" F. F. Lighthall [1990]:

"The weakness in engineering education, in turn, is taken to be of a pervasive genre: An overemphasis in contemporary universities and research centers on specialization and analysis and an under emphasis on synthesis of knowledge across fields. A larger lesson of the accident, then, is that professional narrowness, leading to false diagnosis of cause-effect relations, can be fatal."

From <u>To Engineer is Human, The Role of Failure in Successful Design</u>, by H. Petroski [1985]:

"Some engineers would say it is all a matter semantics and that all structural failures can be traced back to one cause, design error, for even so-called construction errors should be anticipated by the designer. It is true, of course, that all failures can be argued to be the result of design errors, for as the purpose of design is to obviate failure, the failure not anticipated is a clear indication of improper design. But to obviate failure, a designer must anticipate it."

From "Checking Techniques" by Franz Knoll [1986]:

"When we therefore at our schools, free the students from the tedious work of analyzing structural situations by hand, in order to let them spend more time with the screen and type set, we are committing a capital mistake. If this goes on, we shall have killed innovation soon in the field of structural engineering, and mistakes, as they will come out of the black box of the computer, will become increasingly difficult to catch. The computer is the ultimate fool, and we have elevated it to the ultimate authority. What is going to be the price?"

Summary

The central theme that developed from these reviews was consistent. The single largest source of reliability problems associated with structures is HOE. Approximately 80 + % of the "failures" of such systems is due to compounded HOE. HOE occurs in all of the life-cycle phases including design, construction, and maintenance.

In "passive" systems, where the majority of human activities that influence reliability are confined to the design and construction phases, the majority of HOE occurs in the design phase. In "active" systems, where human activities are present in all life-cycle phases including the long-term operating phase, the majority (approximately 80 %) of HOE occurs or is made evident during the operating phase.

Lack of recognition of HOE is the fundamental reason for the disparities between computed or notional reliabilities and actuarial reliabilities.

Another important finding from this review regarded quantitative assessments of the causes of HOE related failures. The review did not identify one source of reliable objective data on HOE related design and construction failures. The studies have been sporadic and subjective in nature. There is no common classification or description of HOE in design and construction. There has been and still is no uniform classifications of errors or a uniform basis for identification of their causes and effects.

The results of this review resulted in a consistent definition of when, where, and how human errors occur in design and construction of non-marine structures. Design errors are important. Design errors occur most frequently in determination of loadings and in design of connections. Construction errors occur most frequently in assembly due to poor erection procedures. The most dominant cause of these human errors is insufficient knowledge resulting from lack of proper training.

The experience with non-marine structures indicates that the challenge of reducing HOE in design and construction is not a problem of not knowing what to do. It is primarily a problem of not doing what we know we should not do.

Chapter 6

HUMAN ERRORS: MARINE STRUCTURES

Causes of Unsatisfactory Quality

Table 6.1 summarizes causes of unsatisfactory quality in some marine structures [Bea, et al., 1994]. Unsatisfactory quality is defined as undesirable or unanticipated poor performance associated with the structures. The unsatisfactory quality identified in Table 6.1 resulted from not only in the catastrophic collapse or loss of the structure (exceed capacity), but as well resulted from unexpected durability problems (insufficient corrosion and fatigue cracking resistance).

The causes of unsatisfactory quality can be organized into three categories (Figure 6.1):

1) those that underlie the actions,

2) the direct initiating actions, and

3) the compounding or propagating actions.

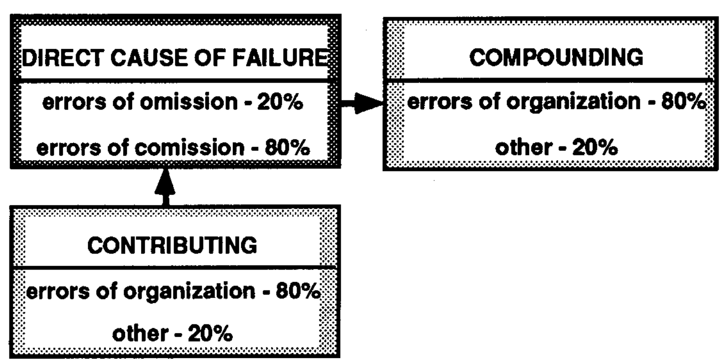

Figure 6.1 - Primary causes of unsatisfactory quality

Often, the direct initiating actions are identified and the more important underlying and compounding actions are ignored.

A detailed study of the case histories summarized in Table 6.1 indicates that while the direct causes of failure can be attributed to the acts of individuals, the dominant contributing and compounding causes are fundamentally "organizational;" erroneous actions by groups of individuals that influence the direct cause of failure and exacerbate or escalate its development through compounded errors [Moore, Bea, 1993b]. Of the individual errors, the majority of errors are errors of commission; what was performed was erroneous and purposefully exe-

cuted. Errors of omission or what was performed was not intentional account for a minority of the causes.

Table 6.1 - Causes of unsatisfactory quality in marine structures

Marine Structure	Causes
Texas Tower #4 [Bea, 1972]	• environmental forces underestimated • unrealistic structure design assumptions • construction modifications due to poor design • damage during installation • unwillingness to acknowledge early warning signals
Camille Platforms [Pate-Cornell, Bea, 1992]	• lack of recognition of environmental conditions • underestimation of environmental forces • excessive risk taking by organization
Alexander Kielland [Moan, 1981]	• structure design not robust; damage intolerant • inappropriate modifications during maintenance • inadequate inspection
Ranger I Jack-Up [Pate-Cornell, Bea, 1992]	• error in design computer program • lack of design checking and verification • inadequate quality assurance in design and construction
Ocean Ranger Semi-Submersible [Moore, Bea, 1993]	• lack of adequate back-up in ballast controls • lack of software on ballast controls • lack of qualified and adequately trained personnel • insufficient life saving equipment and training
Sleipner A Platform [Jakobsen, 1992; Noyes, 1994]	• error in design finite element analysis of cell intersections • non-robust design of star cells and intersections • lack of adequate shear reinforcement in star cells • inadequate quality assurance in design
Piper Alpha Platform [Pate-Cornell, Bea, 1992; UK Dept. of Energy, 1990]	• poor design layout of topsides and risers • inadequate damage tolerance in facilities • poor operating organization • inadequate training
TAPS Tankers [Bea, 1992; Bea, 1993]	• inadequate design of structural details for fatigue • inappropriate use of HTS • poor financial environment • poor construction
Bulk Cargo Carriers [Robinson, 1991, Ferguson 1991]	• cargo loading in seaways under-estimated • inadequate design for durability • inadequate maintenance • poor operation practices (loading, unloading) • inadequate verification / certification environment
Lacey V. Murrow Floating Bridge [Firth, 1992, 1993; Dusenberry, 1993]	• no design for fatigue effects • loss of reinforcement bond • poor maintenance • ignoring early warning signs

Based on the information summarized in Table 6.1, it is apparent that unsatisfactory quality in design, construction, and operations can and does lead to unsatisfactory quality in marine structures. The single largest contributor to these failures can be attributed to unanticipated and undesirable sequences of human and organization errors (HOE). One of the primary objectives of QA / QC measures are to give early warnings of the development of these sequences, make adequate corrections, and allow the system be brought back to an acceptable state of quality.

Human errors have been shown to be the basic cause of failures of many engineered systems [Petroski, 1985; Perrow, 1984; Wenk, 1986; Reason, 1990]. In almost all cases, the initiating event can be traced to a catastrophic compounding of human and organizational errors [Moore, Bea, 1993b; Reason, 1990].

High consequence accidents resulting from HOE can be differentiated into those that occur in design, construction and operation phases of the marine system's life cycle. Unacceptable performance of a marine structure can be the result of improper design and construction of the system. For example, primary contributors to the capsizing of the Alexander Kielland were the lack of redundancy (design flaws) and cracks (maintenance oversights) in the structure [Moan, 1981]. Design flaws originating in the finite element modeling and lack of appropriate review were primarily responsible for the sinking of the Sleipner A platform [Jakobsen, 1992].

Of the three life-cycle phases of a marine structure, the majority of compromises in the quality of the structure occur during the operating phase and can be attributed to errors developed by operating personnel [Bea, 1990; Moore, Bea, 1993a].

A recently published analysis of major claims associated with commercial shipping during 1993 indicated that human errors that occurred during operations were responsible for approximately 62 percent of the major claims (Figure 6.2) [UK P&I Club, 1993].

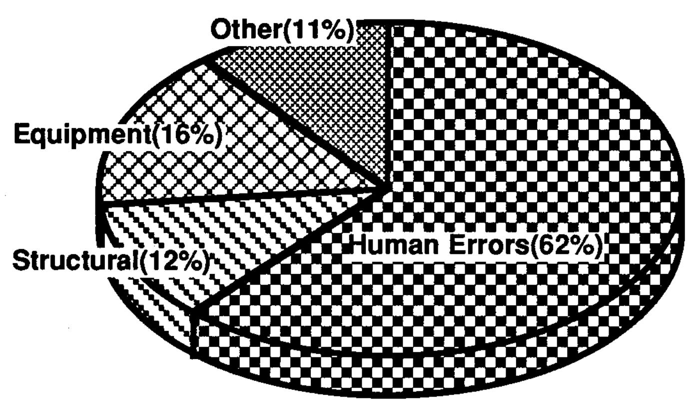

Figure 6.2 - Causes of major (≥ US $ 100,000) claims for all classes of commercial ships 1993

Structural failures accounted for 12 percent and mechanical - equipment failures accounted for 16 percent of the major claims. A substantial of these later "causes" of failure had roots that could be traced directly to operations errors founded in inappropriate maintenance and use.

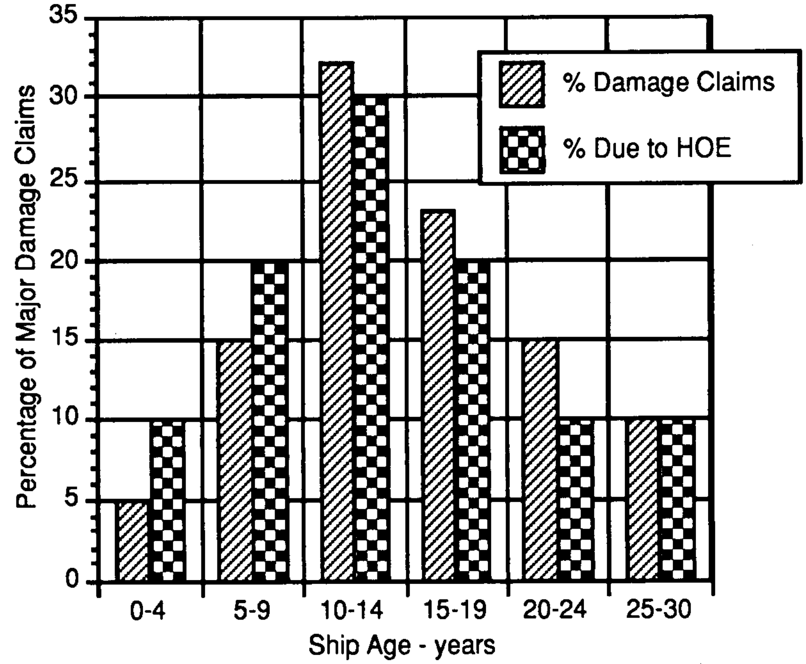

Figure 6.3 - HOE and ship age related to major damage claims

Analysis of the same data with ship age (Figure 6.3) indicates that there is a definite correlation between the age of the ship and the incidence of human errors.

Quoting from that report:

"Why do people persistently make flawed decisions which are at odds with all their training, experience and better judgment? Factors include over confidence, the tendency to respond to commercial pressures at the expense of good practice, personal pride leading to failure to seek assistance, linguistic confusion, and not least, fatigue. Human error is the overwhelmingly dominant factor in claims of all sizes."

"Human errors occur more often in ships of 10 - 14 years old (Figure 6.3). This may reflect manning pressures on ships designed to run with larger crews than is now the practice, or accumulated lack of maintenance prior to the third survey."

"There are sensible recommendations for improved personnel management, the importance of training on the carriage of cargo, the need for adequate manning levels and improved training and motivation for both crew and shore personnel."

The causes of tanker (above 10,000 grt) casualties during the period 1979 through 1990 are summarized in Figure 6.4 [Bea, 1992]. Twenty seven percent of the casualties were due to structural problems with the hull or machinery. The remaining 73 percent of the casualties were due to various forms of HOE.

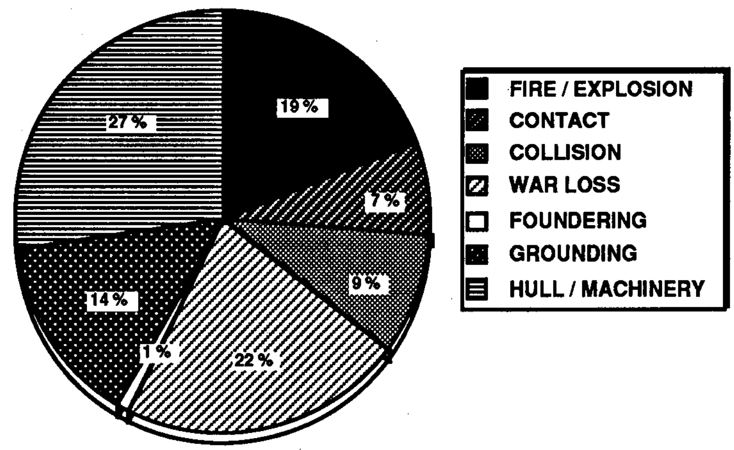

Figure 6.4 - Tanker (above 10,000 grt) casualties 1979 - 1990

A similar current picture has emerged for the operations of both fixed and mobile offshore platforms. Based on information from the World Offshore Accident Databank (WOAD) [Bekkevold, et al., 1990], the principal causes of the accidents to fixed platforms (Figure 6.5) and Mobile Offshore Drilling Units (MODUs) (Figure 6.6) are blowouts, collisions (for MODUs grounding, foundering and towing accidents are included in the rates shown), fires and explosions.

Structurally related causes of severe damage are in the range of 6 % to 9 % of the total causes of accidents for fixed platforms and MODUs, respectively. The generally less robust (damage tolerant) designs of MODUs apparently is responsible for the greater incidence of structurally related severe accidents.

On the positive side of these statistics, it is apparent that the majority of the current compromises in the quality of marine structures that result in severe damage are not centered in the design and construction activities. Further, the majority of the compromises can not be directly attributed to insufficient quality in the structures themselves.

While improvements can be made and are being made in the design and construction procedures and hardware and in the structures themselves, it is apparent that the primary problems with quality in marine structures are centered in operations; how they are used and maintained.

The Piper Alpha fires and explosions, and the grounding of the Exxon Valdez have drawn worldwide attention to the roles of human errors in the operations of marine structures. The public reactions have resulted in the requirements for "Safety Cases" in the United Kingdom sector of the North Sea [Barrell, 1993] and the United States Oil Pollution Act of 1990 (OPA 90) [Moore, 1994].

In the United Kingdom, Safety Case study requirements have also been suggested for commercial ships [House of Lords Select Committee on Science and Technology, 1992]. These reactions have had important effects worldwide on how quality in the marine structures is achieved and maintained. The OPA 90 requirements for double- hull tankers operating in United States waters and the liabilities placed on transporters of hydrocarbons for pollution are a legacy of regulatory reaction to the Exxon Valdez.

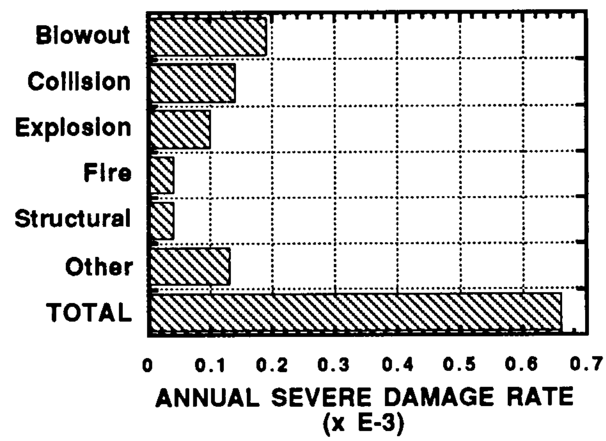

Figure 6.5 - Initiating events leading to severe damage to fixed offshore platforms

Two recent important international steps have been taken to help improve quality in operations of ships. The first is the development of the International Management Code for the safe operation of ships and for pollution prevention by the International Maritime Organization (IMO) [IMO, 1993]. The second is development of the quality system for requirements for classifications societies by the International Association of Classification Societies (IACS) [IACS, 1991].

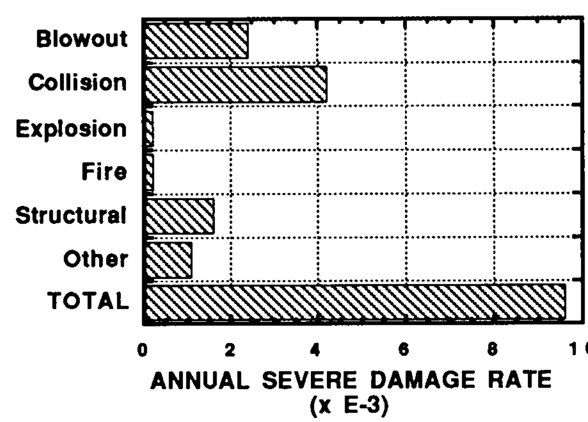

Figure 6.6 - Initiating events leading to total loss of mobile offshore platforms

These steps have been accompanied by a series of important technical developments that address the quality of operations of commercial ships.

- Development of a comprehensive structural and equipment IMR management strategies and systems [Bea, 1992; Melitz, 1992],
- Development and implementation of hull condition monitoring and ship routing - navigation systems to assist in IMR and other aspects of operations [Brooks, 1992; Brooking et al., 1992; Lewis et al., 1991; Chen, 1987], and
- Development of qualitative and quantitative process and procedures to help evaluate alternatives to improve the human factors related aspects of operations [Moore, Bea, 1993b, 1993c; Reason, 1991; Moore, Bea, Roberts, 1993].

In a recent study of the safety of ships, the Select Committee on Science and Technology of the House of Lords [1992] observed the following:

"Modern science and technology are not being adequately applied in many of the fields which affect the safety of ships."

"Shipping must not be allowed to become a victim of its own long history: we consider that the time has come for radical change."

This study developed two primary long-term recommendations for the shipping industry:

1) Primary safety goals for all aspects of ship operations: These would consist of standards of structural strength, stability, maneuverability, performance in a seaway, operational competence and safety management for every type of ship operation. They would be based on quantified assessment of risk, on analysis of costs and benefits, and on international agreement as to what level of risk was acceptable.

2) A safety case for every ship trading commercially, produced by the operator and approved and audited by the flag state: The safety case would demonstrate that the ship's operations would achieve the relevant primary safety goals, subject to prescribed conditions. These conditions would cover matters including maintenance, protective coatings and levels of corrosion, safety equipment; manning levels and crew competence; loadline and rates of loading, and unloading; stresses on the hull, navigation and communications equipment; and safety management system. The safety case would be completely reviewed every 5 years in the light of changes in the ship's operating pattern and in the conditions of the ship.

In 1989, following several serious tanker accidents which were clearly caused by human error and a growing awareness in the maritime community of the human factors, the IMO adopted an Assembly Resolution committing the Marine Safety Committee and Marine Environmental protection Committee to examine the "human element" as a cause of marine casualties.

In the past four years, this initiative has become, within IMO, a major, broad-based long-term effort involving all of the technical sub-committees, and in which nearly all tasks and developments are being examined in a human factors light. This initiative has produced the International Management Code for the Safe Operations of Ships and Pollution prevention (or International Safety Management - ISM Code). The ISM Code is to be adopted as a new requirement within the SOLAS Convention. The premise behind the ISM Code is to set rules and standards for the organization of a company management with respect to safety and pollution prevention thorough the development of a safety management system (SMS). ISM Code compliance will be required for both the company and each vessel under the company's operation and is expected to have far reaching effects on ship owners and operators (Moore, McIntyre, 1994).

In a similar vein, the International Chamber of Shipping and the International Shipping Federation has recently (August 1993) issued a draft International Safety Management Guideline titled "Application Guidelines for the IMO International Safety Management (ISM) [Int. Chamber of Shipping, 1993]. The ISM introduced a Safety Management System (SMS) that requires a company to document its management procedures to ensure that "conditions, activities and tasks, both ashore and on board affecting safety and environmental protection, are planned, organized, executed and checked in accordance with legislative and company requirements."

Documented SMS procedures are developed to cover: 1) objectives and applications, 2) safety and environmental protection, 3) company responsibilities and authorities, 4) designated persons, 5) Master's responsibility and authority, 6) resources and personnel, 7) shipboard plans, procedures, and instructions, 8) emergency preparedness, 9) reports and analysis of accidents, 10) maintenance of the ship and equipment, 11) documentation of results, and 12) company verification and evaluation. Three key documents embody this system and include a shipboard emergency contingency plan, a shipboard safety management manual, and a SOLAS training manual.

The U. S. Coast Guard has identified six fundamental requirements for an SMS:

- A safety and environmental protection policy.
- Instructions and procedures to ensure safe operation of ships and protection of the environmental in compliance with relevant international and Flag State legislation.
- Defined levels of authority and lines of communications between, and among, shore and shipboard personnel.
- Procedures for reporting accidents and non-conformities with the provisions of the Code.
- Procedures to prepare for and respond to emergency situations.
- Procedures for internal audits and management review.

Moore and Roberts [1994] have reviewed and summarized these recent developments.

These are obviously different approaches intended to help reach the same objective; acceptable quality. The House of Lord's Safety Case Study approach is highly quantitative and based on detailed evaluations of existing and proposed systems. It would strain the resources of industry to perform such evaluations and the implementation would be similarly difficult. The ISM SMS is very qualitative and based on general evaluations. Critical evaluations of existing and proposed systems are not developed. One approach emphasizes documentation

while the other emphasizes the processes of evaluation. They both represent current attempts by this segment of the marine industry to improve quality and safety.

These developments have paralleled by a very similar series of developments that pertain to the operations of offshore platforms. Industrial and regulatory guidelines are being revised to address both the system and the human related aspects [Sutherland, 1991; Bea, 1993; Barrell, 1993; Hashemi, 1991; Fitzerald, et al;, 1991; Technica, 1983; Cox, Walter; 1991; U. S. Dept. of Commerce, 1985; Andersen et al., 1983; Vinnem, Hope, 1992; Bea, et al., 1992].

As a result of the Exxon Valdez accident, the U. S. Coast Guard initiated a formal human factors research and development program [Sanquist, et al. 1993]. This program is addressing the five following general areas: (1) manning, qualifications and licensing, (2) automation design, (3) safety procedures and data, (40 communications, and (5) organizational practices. The topics being addressed in each of the five areas are summarized in Table 6.2

Table 6.2 - U. S. Coast Guard human factors research and development program

Manning, qualifications, licensing	Automation	Safety Method and Data	Communications	Organizational Practices
• job requirements • use of simulators • experience factors • automation impacts	• cognitive impacts • training • bridge workloads • alarm systems • information distribution • electronic navigation • Vessel Traffic Systems (VTS)	• investigations • human factors inspection procedures • spill response organization	• technical and organization procedures • aids to navigation • VTS communications	• personnel fatigue • organizational policy • OPA '90 impacts

Examples of HOE in Design & Construction

The following case histories have actually occurred. The author has had personal involvement in these case histories and hence has intimate knowledge of the details. The background from these experiences was used as one of the bases for the research reported by Paté-Cornell and Bea [1989, 1992]. The objective of relating these examples is to illustrate some of the aspects of how HOE can influence the design and construction of marine structures.

The Sliding Platforms. In 1966, an offshore lease was purchased. The site surveys indicated an unusual bathymetry. An initial evaluation indicated the potential for mud slides. A study was initiated in 1967 to investigate this phenomenon and evaluate the risk. The design of a conventional platform was

commissioned (1967) on the premise that if the risk of mudslide was found to be too high, the platform would be sited elsewhere and a mudslide resistant platform would be designed for the location.

The design was completed before the risk study. The management made the decision to start the construction of the platform so that if the study indicated that the site was safe, the project would be on schedule.

The risk study, when it was completed, confirmed the presence of mud slides and indicated that the risk of failure at the proposed site was ten to a hundred times greater than for a conventional site. The recommendation was made not to site a conventional platform at the proposed location.

The management and the technical team met to discuss these recommendations. A technical report was written stating that if a conventional platform was installed at the site, it would fail in a short period of time due to overloading by mudslide forces. The management, however, made the decision to site the conventional platform at the proposed location. The lead engineer refused to sign the final construction drawings.

One platform was knocked to the sea floor, and an adjacent platform moved down-slope during a storm in August 1969. The sliding around the adjacent platform was discovered when workers tried to run tools through the well conductors. Laser survey of the piles disclosed significant platform movement had occurred. The still standing platform was then declared a constructive loss and an insurance claim was made. Both platforms, however, were salvaged.

The managers involved in the decision suffered career by-pass and eventually left the company. These managers stated that they never believed in the slide hazard. The technical staff involved suffered the opposite type of credibility crisis: management after this episode started believing them too much without asking questions.

Analysis: The sequence of errors came from an organizational commitment made without proper information. When this information became available, the time pressures were such that the management had strong incentives to dismiss it. By then, it had lost a lot of its value due to poor timing. The result is a culmination of errors of judgment that can be described as follows:

(1) a very risk prone attitude in the decision to begin the work without the tests' results, and
(2) a refusal to use the information when it became available because it revealed that the previous move was a mistake.

The Homeless Mobile Drilling Rig. During the winter of 1979, a mobile drilling unit originally designed for the storm conditions of the Gulf of Mexico, was proposed for siting in Lower Cook Inlet, Alaska. The platform, located offshore of California, was preparing for transfer to Alaska. The client oil

company contacted a consultant to make a risk assessment for siting the platform in Alaska.

Data were gathered on site conditions as well as the conditions of the unit, looking for fatigue damage to the legs from long tows. A risk assessment was made and the results were compared to risks of the same unit during the storm season if it were sited in the Gulf of Mexico. The results indicated that the risk in Alaska was ten times greater than in the Gulf of Mexico.

In particular, the consultants recommended not to site the units during the proposed period but, rather, two or three months later when the chances of storms and icing are lower. The client oil company did not want to wait because of the costs involved ($100,000 per day) in putting the unit on standby for two or three months.

The client decided to discuss the risk of siting with the rig owner, the rig operator, the rig classifier, the rig mover, and the rig insurer. The risk assessment was presented to this decision making group and a report written summarizing the results.

The group decided that the risk was too great to site the rig during the initially proposed period and the decision was made to delay the siting until after the winter storm season. The group asked the consultant if they really believed their risk assessment results, which the consultant confirmed. The client required the presence of the consultant onboard during the starting of operations, as one's perspective on risk may change as a function of one's proximity to it.

The unit operated without incident and was later taken to Norton Sound, Alaska. The risk assessment was then repeated, this time with respect to scour around the rig's footing. The results indicated that the probability of scour was high. The unit was placed in Norton Sound. Footings' scour did occur and protection had to be placed in order to prevent damage to the rig. Two divers were killed during the placement of the scour protection. The unit was then towed from Norton Sound to California. During the transit, a mysterious flooding occurred and the unit sank in the Aleutian trench in 6,000 ft of water.

Analysis: The fundamental error here is again one of bad judgment, this time, the failure to consider a particular type of external event (scour) that later threatened to cause platform failure. It is an information error that was probably induced by earlier difficulties and costs due to the relocation of the structure.

It seems that the decision makers, having already experienced the costs of the prudent decision to delay the Alaska siting, did not want to know more about potential problems. The final error can be traced to a refusal of information and a breakdown in communications.

The Upside Down Platform. A platform steel jacket was designed to be launched from a floating barge and towed to the platform site. The jacket weight and buoyancy were checked to determine if the jacket would float after launch-

ing. The calculations indicated that additional buoyancy tanks were needed to make the jacket float. Buoyancy tanks were added and placed at the upper face of the top end of the jacket. The jacket was launched, but because of very high momentum when the jacket rotated, the jacket buoyancy at the upper face of the top end was ineffective at slowing the jacket's movement. The jacket embedded upside down. The buoyancy was insufficient to raise the top of the jacket that had more stability upside down. The closure plates of the legs leaked due to bad welds and the reserve buoyancy was lost. Due to bad weather, it took two months and a lot of money to right the jacket.

The next engineer who designed a similar structure decided to launch it in deep water fifteen miles from the intended location then to tow it to the site. During the tow, the jacket swung against the towing barge and crushed two legs. The jacket had to be towed into shallow waters to expose the legs. The damaged portions of the legs had to be cut out and new sections were welded in. In trying to correct the first error, a second error had been committed that added to the costs of the first one.

Analysis: This is a case of gross error due to lack of experience. Although some checking did occur and an initial defect was revealed, the corrective action that followed was insufficient to fix the problem.

The second error was a repeat of the same phenomenon. Both errors were cases of wrong understanding (i.e., wrong models) of the dynamic behavior of the structure during the launch and during the tow.

Sleipner A Finite Element Error

The Sleipner A platform failure is a prime example of a recent marine structural failure due to HOE that occurred during the design [Jakobsen, 1992]. This design error had catastrophic consequences during construction. During a ballast test operation in August 1991, the Sleipner A Gravity Base Structure (GBS, Figure 6.7) sank to the bottom of a fjord in 200 meters of water outside Stavanger, Norway.

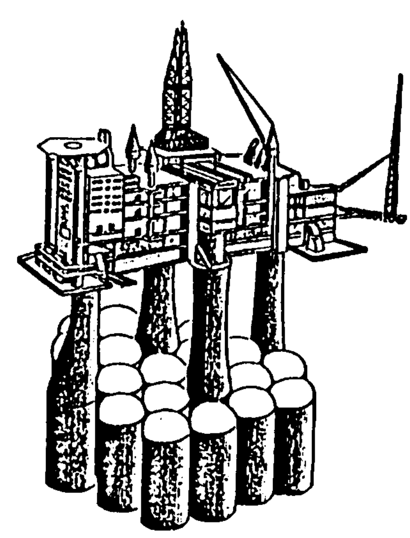

Figure 6.7 - Sleipner A GBS

The GBS had been constructed by Norwegian Contractors (NC) over the previous 2 years. The base of the structure had been ballasted to a depth of 97.5 meters prior to deck mating. This was the deepest submergence that the platform was intended to experience.

A deep bang-like sound occurred in the D3-shaft (Figure 6.8). The sound was followed by a sound of running water from the direction of the D3

shaft. Investigation of the shaft was undertaken and water was first seen entering above the intended ballast water level at the star-cell intersection (Figure 6.8). Emergency deballasting was started by pumping water from three of the cells surrounding the D3 shaft, but the pumping could not keep up with the sinking.

Approximately 8 minutes after the first bang, the order to abandon the platform was given. The people aboard the platform were evacuated. The platform disappeared from the surface. The base cells imploded and the platform became a pile of concrete rubble on the floor of the fjord.

The Sleipner A platform was the twelfth in a series of Condeep GBS platform built by NC. It was a typical GBS with 24 caisson cells over a base area of about 16,000 square meters. The technology for the design and construction of this platform were well established and proven.

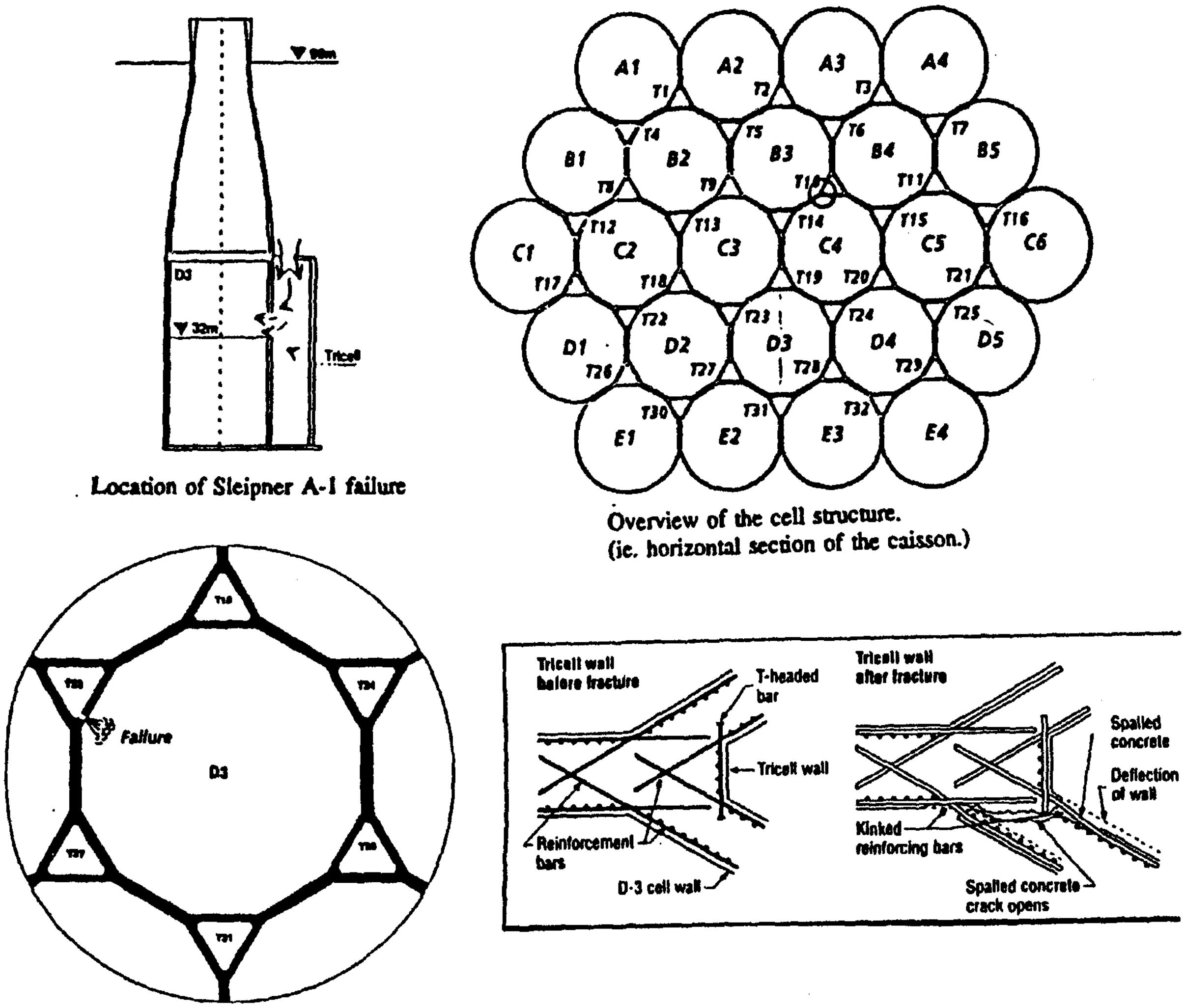

Figure 6.8 - Details of the Sleipner GBS base cells and tri-cell intersection reinforcement and failure

An extensive investigation concluded that the primary causes of failure were as follows [Jakobsen, 1992; Rettedal, Gudmestad, Aarum, 1993]:

a) Direct Cause - the global finite element analysis used to calculate sectional forces gave a 47 percent under-estimation of the shear forces in the tricell walls. The error was caused by use of a coarse finite element mesh with some skewed elements used for analysis of the tricell walls. The lower design forces resulted in lack of shear reinforcement in portions of the cell and tricell joints.

b) Compounding Causes - reinforcement was improperly detailed in the tricell joints. The T-headed shear reinforcement bars were detailed too short and were anchored in a tension zone (Figure 6.8). The conventional, but difficult to install stirrup reinforcement was omitted from the joint. The tricell joints were not designed or checked as separate components. The same reinforcement designed for the cell walls was continued through the tricell joints. Testing subsequent to the failure confirmed the inadequacy of the reinforcement.

c) Contributing Causes - similar failures of the tricell joints had occurred in previous GBS. The problem had been detected and remedied before it had become catastrophic. However, all of the personnel involved in these earlier problems were not involved in the Sleipner A design and construction. There was a "loss of corporate memory". In addition, because the design and construction had become so "well established", and because of time and budget limitations, detailed and over-view checking had been curtailed.

Following the sinking of the Sleipner A GBS, a number of studies and steps were taken to prevent a mistake of such magnitude from occurring again [Rettedal, et al., 1993]. Extensive physical testing of the tricell joints were performed. The geometry of the tricell was changed. There were extensive and careful finite element analyses performed of the joint. These analyses were calibrated and verified with the results from the physical tests on the joint.

In addition, revised design guidelines and regulations were implemented. There was a considerable increase in independent design checking and verification. The revised design guidelines and regulations included an increase in the design load factor for water pressure, a new concrete design code shear capacity formula, stricter water tightness criteria, larger concrete cover on reinforcement, stricter tolerances on reinforcement placement and more transverse reinforcement required, structure would be designed to with stand a 100-year summer storm load in the installation phase, vertical prestressing cables were to be used in all shafts to minimize tensile loadings and cracks (developing a "robust" or damage tolerant structure), and double barriers for all openings and penetrations in the base cells.

The changes made in the design process were primarily intended to provide added capacity and robustness. Extensive Quantified Reliability Analyses

(QRA) were performed to identify how and where to place design safeguards [Rettedal, Gudmestad, Aarum, 1993].

Most notable of the changes was a 400 % increase in the total man-hours for verification and checking work. In the wake of a major accident which "should not have happened," there is little tendency to view added safety precautions as overkill. Due to the delays caused by the failure, there were extreme pressures to develop a replacement platform as soon as possible. With time of the essence and the memory of the failure fresh, the increased safety measures were readily included in the design, rather than evaluated as to their necessity.

The platform was re-designed and re-built by NC. It was successfully installed two years after the failure of Sleipner A. The total cost of the failure was estimated to be in excess of $ 1 billions (U. S.).

In Chapter 9, two studies will be discussed that address quantitative evaluations of how to improvement management of HOE in the re-design of the Sleipner A platform.

Classifications of Sources of Errors

Factors that contribute to human errors can be categorized into organizational, individual, and systems (hardware, software) errors. Organizational influences have been found to have profound impacts on operational quality of marine structures [Perrow, 1984; Bea, Moore, 1991; Embrey, 1991; Reason, 1991; Robinson, 1991]. Individual or human errors are those which are made by a single person which can contribute to an accident. The chain of events which led to the Occidental Piper Alpha accident were initiated by events leading from an unfinished maintenance job in the gas compression module [UK Dept. of Energy, 1990]. Their escalation could be directly attributed to a wide variety of organization errors including corporate decisions made regarding manning, relief supervision, the supervision of work crews, and the provision of production incentives [Martin, 1991].

A similar chain of contributing and compounding causes firmly founded in organizations can be identified in the grounding of the Exxon Valdez (Moore, 1994; Moore, Bea, Roberts, 1993). This compromise in acceptable quality was not fundamentally a failure rooted in structural and equipment systems, but in organizational systems [Wenk, 1983]. The contributing and compounding errors directly involved the responsible regulatory and industrial organizations [Moore, 1994; Moore, Bea, Roberts, 1993].

Experience indicates that the influences of the organizations on the reliability of marine systems generally is the most pervasive of the human factor related causes of accidents (Figure 6.1). High reliability organizations inherently develop high reliability operators, systems, and operations (and vice versa) [Roberts, 1989; Roberts, 1993; Koch, 1993]. High reliability organizations gen-

erally focus on the long-term quality of production, not on the short-term quantity of production. High reliability organizations generally take long-term views and found their short-term activities on their ability to develop long-term quality productivity. Low reliability organizations focus on short-term gains and productivity [Koch, 1993].

The sources of organization errors can be placed into three general categories [Moore, Bea, 1993b; Moore, 1994]. The first is upper level management. The lack of appropriate resources and commitments to achieve reliability and the provision of conflicting goals and incentives (e.g. maintain production when it needs to be decreased to allow maintenance to be performed on the system) are examples of upper level management errors. The second is front line management. Information filtering (make it look better than it really is, tell the boss what he wants to hear - good news), and redirection of resources to achieve production at the expense of safety are examples of font line management errors.

The third category is the design, construction, or operating team. Team work in which there is an inherent and thorough process of checking and verification have proven to be particularly important: "if you find a problem, you own it until it is either solved or you find someone to solve it" [Roberts, 1993]. The lack of team work represented in poor communications between work shifts (ineffective permit to work systems) or between work teams and the platform control room have resulted in several major accidents [Embrey, 1991; Sutherland, 1991]. Communications break-downs and errors caused by languages and cultures are a common source of accidents in ship operations involving crews of various nationalities [Gathes, 1989; UK P&I Club, 1993].

Errors can also be observed with human-system (equipment, structure, software or instructions manuals) interfacing. These are described as system (hardware) errors and procedure (software) errors. System errors can be attributed to design errors and result in an operator making improper decisions. Similarly, the procedures and guidelines provided to design, construct, or operate a system can be seriously flawed. System errors led to the loss of the ballast control aboard the Odeco Ocean Ranger [Paté-Cornell, Bea, 1989; Moore, Bea, 1993a] and emergency system failure aboard the Occidental Piper Alpha [UK Dept. of Energy, 1990; Martin, 1991]. Appropriate operating manuals on how to interrupt potentially catastrophic sequences were almost totally lacking in both of these cases.

Several design errors have recently been traced to design guidelines and design software that were seriously flawed [Moore, Bea, 1993b; Pate-Cornell, Bea, 1989; Jakobsen, 1992]. Unnecessary complexity and insufficient checking had embedded serious software "bugs" that resulted in serious design errors.

In 1993, the American Petroleum Institute issued the first edition of LRFD guidelines for design, construction, and maintenance of offshore platforms: API RP 2A - LRFD.[1] At the same time these guidelines were issued,

[1]This effort required 15 calendar years and an estimated 10 man-years to complete.

substantial changes were made in the design procedures and guidelines to determine hydrodynamic forces. These procedures represented a major technical step forward in detailing how engineers could determine storm loadings acting on offshore platforms.

Experienced engineers that were faced with implementation of these guidelines made several dramatic mistakes in initial applications. Their experience with WSD did not "translate" to a similar feeling for LRFD results. The complexity of the revised hydrodynamic force guidelines also resulted in several dramatic over-estimates of the design forces. Engineers would not in general take advantage of a variety of load-reduction parameters in the formulation. The engineers were not properly trained or given sufficient resources of time and assistance to overcome the problems of these initial applications.

This experience suggests that when new design guidelines and codes are developed, thought and detailed considerations should be given to the implementation and QA / QC aspects (implement TQE). The author has observed the need for similar considerations in development of the ISO versions of the API RP 2A guidelines. Engineers bent on "progress" and not founded in consideration of the "human" aspects generally have little patience for nor regard for such considerations. The best technology is not necessarily the most complex technology. Elegant simplicity and clarity need to be emphasized if one is to avoid embedding errors and error promoting procedures in design guidelines.

The external and internal environments can contribute to the error producing potential of the humans that design, construct, and operate marine systems. External environmental factors such as darkness, extreme low temperatures, and extreme storms can exacerbate human error producing potentials [ASTM, 1993; Miller, 1990]. Similarly, internal environmental factors such as poor visibility, smoke, and intense motions can cause errors [Martin, 1991; Moore, Bea, 1993b].

Human and organization interrelationships with systems, procedures, and environments (internal, external) can be organized as shown in Figure 6.9 [Hawkins, 1987]. There are error producing potentials within each of the primary sectors including the human operators (designers, constructors, operators), the organizations that influence these operators, the systems themselves (hardware), the documentation that embody the manuals of use or practice for the systems (software), and finally the external and internal environments. In addition to the error producing potentials within each of these sectors, there are error producing potentials at the interfaces of the sectors [Reason, 1991; Roberts, 1993].

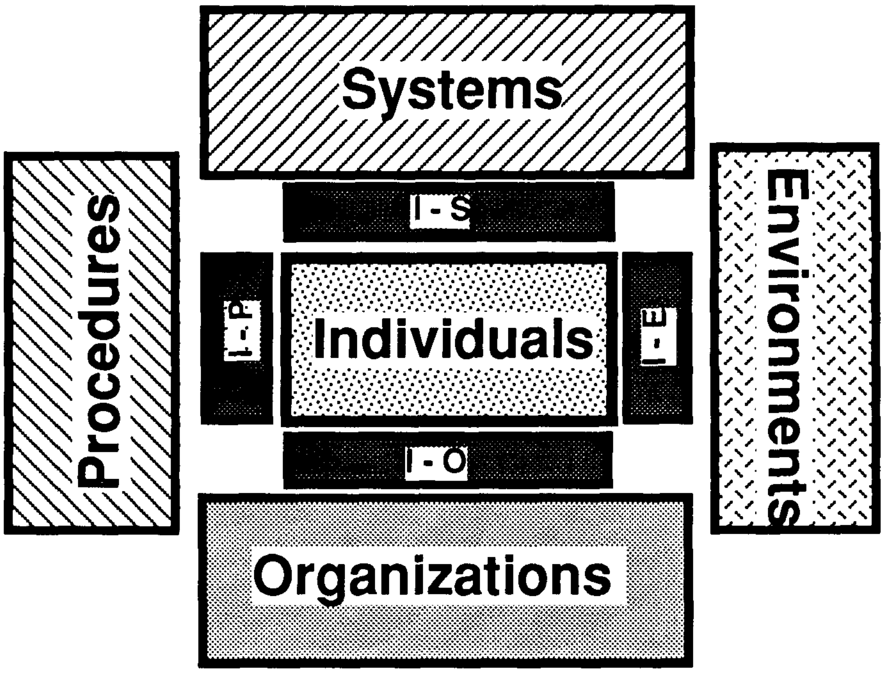

Figure 6.9 - Components and interfaces that can lead to human errors resulting in undesirable quality

Human Errors

Human errors can be described as actions taken by individuals that can lead an activity (design, construction, operation) to realize a lower quality than intended. These are errors of commission. Human errors also include actions not taken that can lead an activity to realize a lower quality than intended. These are errors of omission.

Human errors might best be described as "actions and inactions that result in lower than acceptable quality" to avoid implications of blame or shame. Human errors also have been described as "misadministrations." and "unsafe actions."

Human errors can be described by types of error mechanisms (Reason, 1990). These include slips or lapses, mistakes, and circumventions. Slips and lapses lead to low quality actions where the outcome of the action was not what was intended. Frequently, the significance of this type of error is small because that these actions not being as intended are easily recognized by the person involved and in most cases easily corrected.

Mistakes can be developed while the action was as intended, but the intention was wrong. Circumventions (or violations) are developed where a person decides to break some rule for what seems to be a good (or benign) reason to simplify or avoid the task.

Mistakes are perhaps the most significant because they are being followed purposefully by the user who has limited clues that there is a problem. Often, it takes an outsider to the situation to identify mistakes.

Circumventions are potentially significant contributors to risk because these conditions can result from unexpected combinations of errors and circumventions.

Based on a study of major unanticipated compromises of acceptable quality involving marine structures, Table 6.3 summarizes the primary factors which have resulted in individual errors. The error factors range from those of judgment to ignorance, folly, and mischief [Wenk, 1986]. Inadequate training is a primary contributor to many of the past failures of marine structures. Fatigue combined with boredom have played a role in many of the accidents [Gates, 1989; Pollard, et al, 1990; Panel on Human Error in Merchant Marine Safety, 1976].

Table 6.3 - Human error factors

Fatigue	Wishful thinking	Bad judgment
Negligence	Mischief	Carelessness
Ignorance Panic	Laziness Violations	Physical limitations
Greed	Drugs	Boredom
Folly Ego	Inadequate communication	Inadequate training

Human errors are magnified and compounded in times of extreme pressure [Panel on Human Error in Merchant Marine Safety, 1976; Martin, 1991]. Pressure results from a combination of task complexity, training in performance of the task, the required task precision, psychological stress, intensity of distractions, and the severity of impairments.

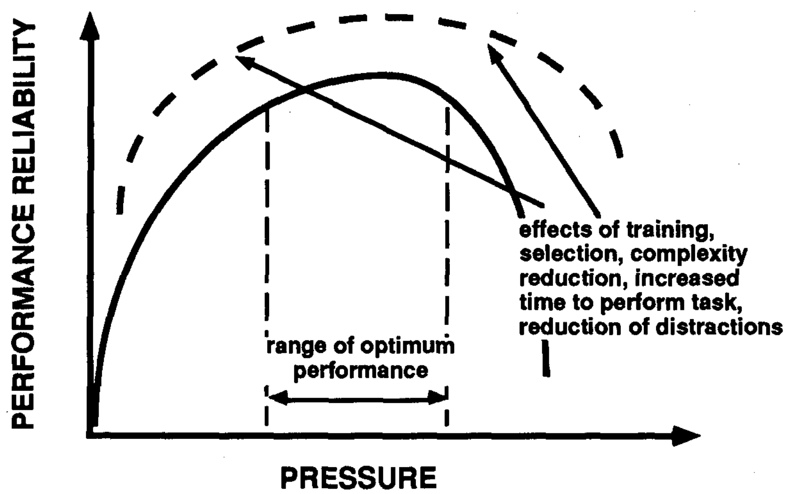

Figure 6.10 - Effects of pressures on human performance

As shown in Figure 6.10, optimal performance levels are observed at an "appropriate level of arousal." There is a marked and rapid decrease in the performance reliability after the optimum pressure has been passed. The human performance levels

vary between individuals depending upon training, variability between individuals, organizational pressures, and complexity of the operating system.

Nevertheless, performance is observed to deteriorate when pressure levels are either too low or high. For example, times of high pressures could be effected by stress or panic while low human performances could be the result of boredom or laziness. Both extremes can contribute to increase the incidence of human errors.

A mishap is differentiated into three psychological stages: perceiving, thinking, and acting (Figure 6 .11) [Bea, Moore, 1992; ASTM, 1993]. The danger threshold could be reached by either a lack of sufficient time to react, or errors in perception, thought or action which would either lengthen the time between events or increase the magnitude of the danger buildup. The perception stage starts with a mishap and is followed by a warning. The warning is then noticed and leads to recognition of the mishap source. The thinking stage begins with the identification of the problem and information (whether complete or incomplete) is processed at this stage to evaluate decisions for the best course of action. The mishap is acted upon with execution of a plan and the system is returned to a normal operating status or escalates to a dangerous state.

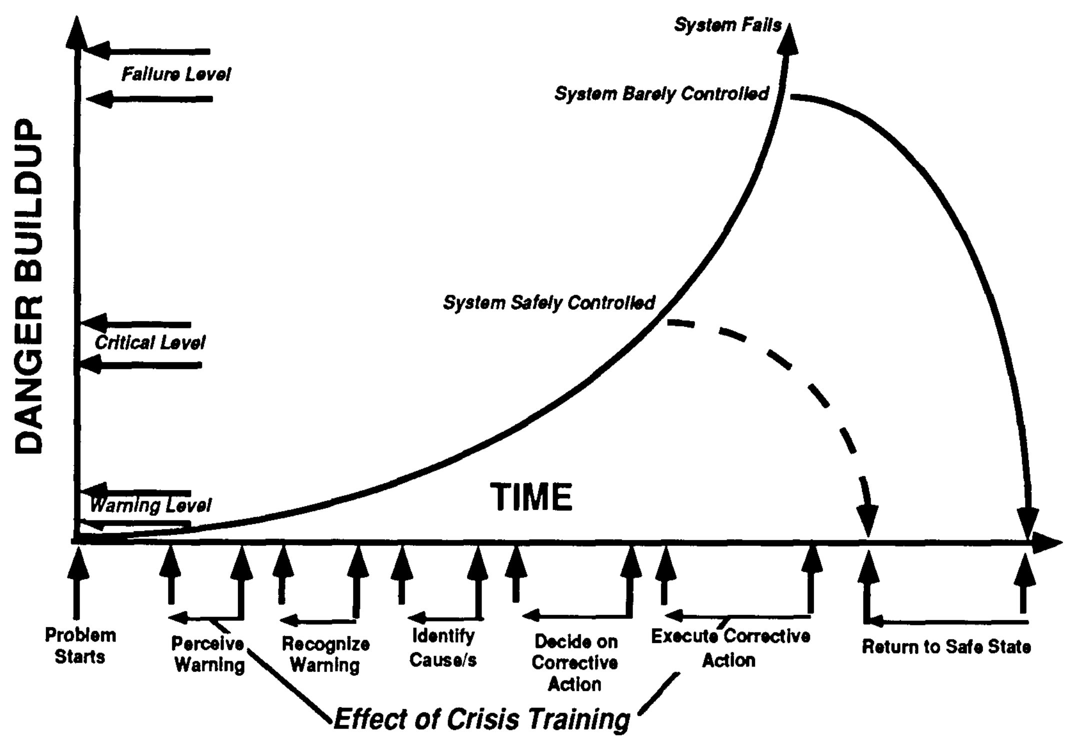

Figure 6.11 - Effects of personnel selection & training on crisis management

Human intervention is responsible for near misses. Humans intervene to interrupt potentially catastrophic combinations of actions and events to bring systems back to within the safe operating zone. Experience indicates that there are generally many more near misses than there are major accidents. If recognized, information on near misses can provide valuable information to prevent direct hits [Reason, 1991]. Personnel selection and crisis training can have marked influences on an individual's or team's abilities to return a system to a safe state [Sutherland, 1991].

Based on a study of available accident databases on marine systems and study of case histories in which the acceptable quality of marine systems has been compromised, the primary factors which can result in human errors are identified in Figure 6.12 [Bea, Moore, 1994].

This human error classification (taxonomy) is intended to allow the exclusive and exhaustive identification of how individuals can make errors in the design, construction, and operation of marine structures.

The sources of mistakes or cognitive errors are further detailed in Figure 6.13.

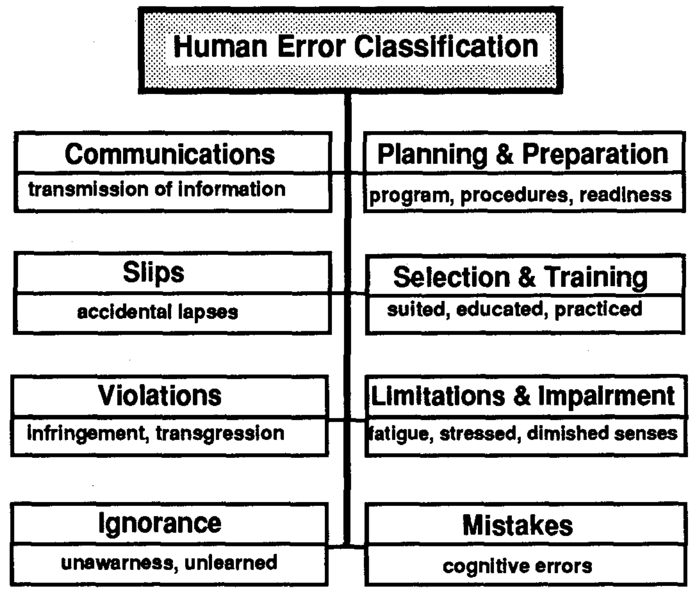

Figure 6.12 - Classification of human errors

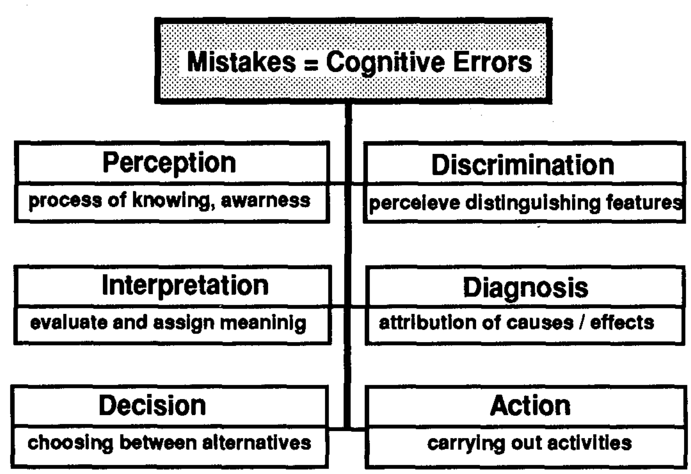

Figure 6.13 - Classification of cognitive errors

Organization Errors

Analysis of past decisions regarding the design, construction, and operation of marine structures provides numerous examples of instances in which organizational failures have resulted in failures of marine systems [Wenk, 1986; Pate-Cornell, Bea, 1989; 1992; Petroski, 1985; Perrow, 1984]. Either collections of individuals (organizations, teams) or individuals (unilateral actions) contribute to accident situations. Failures can occur as a result of an organization's or an individual's willingness to take a calculated risk. Failures can result from different types of inevitable errors that can be corrected in time, provided they are detected, recognized as errors, and corrective action is promptly taken [Roberts, 1993]. Failures can also occur as the result of errors or bad decisions, most of which can be traced back to organizational malfunctions.

Table 6.4 summarizes the primary factors which can have negative effects on organizational reliability. For example, the goals set by the organization may lead rational individuals to conduct operations aboard a platform in a manner that corporate management would not approve if they were aware of their reliability implications. Similarly, corporate management, under pressures to reduce costs and maintain schedules, may not provide the necessary resources required to allow adequately safe operations.

Table 6.4 - Organizational error factors

Time pressures	Low quality culture	Negative incentives
Cost - profit incentives	Low worker morale	Poor communications
Violations Ego	Ineffective monitoring Complex structure	Poor planning / training Rejection of information
Ineffective regulatory requirements	Inequitable promotion - recognition	Production orientation

Generally, two classes of problems face an organization in making collective decisions that result from sequences of individual decisions: information (who knows what and when?), and incentive (how are individuals rewarded, what decision criteria do they use, how do these criteria fit the overall objectives of the organization?). In development of programs to improve management of HOE, careful consideration should be given to information (collection, communications, and learning) and incentives, particularly as they affect the balancing of several objectives such as costs and safety under uncertainty in operations of offshore platforms.

The structure, the procedures, and the culture of an organization contribute to the safety of its product and to the economic efficiency of its risk management practices. The organization's structure can be unnecessarily complex and demand flawless performance [Koch, 1993]. This can result in little or no credible feedback to the upper levels of management. The resulting safety prob-

lem is that there may be inconsistencies in the decision criteria (e.g. safety standards) used by the different groups for various activities. This can result in large uncertainties about the overall system safety, about the reliability of the interfaces, and about the relative contribution of the different subsystems to the overall failure probability.

Organization and management procedures that affect system reliability include, for example, parallel processing such as developing design criteria at the same time as the structure is being designed, a procedure that may or may not be appropriate in economic terms according to the costs and the uncertainties.

Experience indicates that one of the major factors in organizational error is the "culture" of the organization [Roberts, 1989; 1993; Koch, 1993]. For example, the dominant culture may reward risk seeking (flirting with disaster) or superhuman endurance (leading to excessive fatigue), an attitude that in the long run may prove incompatible with the objectives of the organization. Another feature may be the lack of recognition of uncertainties leading to systematic biases towards optimism and wishful thinking.

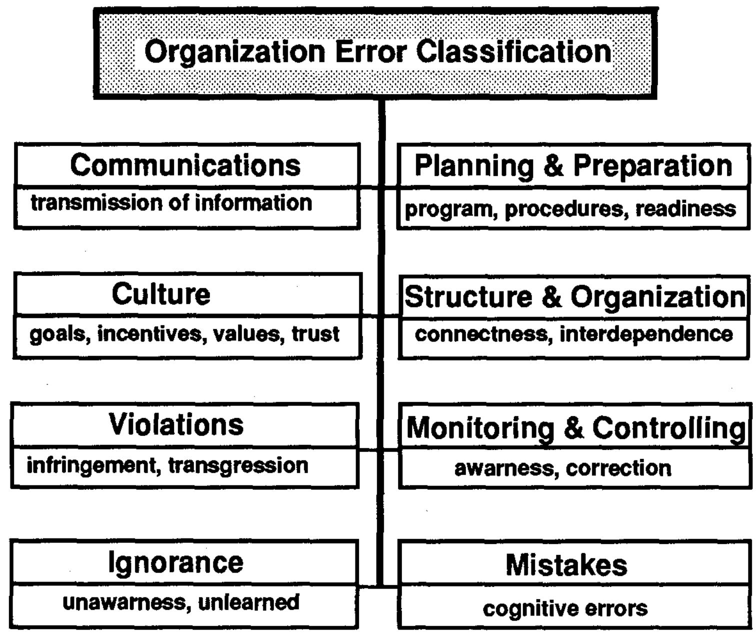

Figure 6.14 - Classification of organization errors

Organization error is a departure from acceptable or desirable practice on the part of a group of individuals that results in unacceptable or undesirable results. A summary of the principal factors that can contribute to or result in organization errors is given in Figure 6.14. Total Quality Management (TQM) philosophies, practices, and procedures have been developed primary to address the human and organizational aspects associated with achieving quality in goods and services [Ashley, Perng, 1987].

System & Procedure Errors

Errors can be initiated by or exacerbated by poorly engineered systems and procedures that invite errors [Miller, 1990; ASTM, 1993]. Such systems are difficult to construct, operate, and maintain. Table 6.5 summarizes system and procedures factors and flaws which can affect the quality of marine systems.

New technologies compounds the problems of latent system flaws. Complex design, close coupling (failure of one component leads to failure of other components) and severe performance demands on systems increase the difficulty in controlling the impact of human errors even in well operated systems.

Table 6.5 - System & procedure error factors

Complexity	Latent flaws	Severe demands
Close coupling	Small tolerances	False alarms
Lack of robustness	Inaccessibility	Incomplete software
Incorrect signals	Difficult maintenance	Poor visibility

Emergency displays have been found to give improper signals of the state of the systems. Land based industries can spatially isolate independent subsystems whose joint failure modes would constitute a total system failure. System errors resulting from complex designs and close coupling are more apparent due to spatial constraints aboard ships and platforms. The field of "ergonomics" has largely developed to address the human - machine or system interfaces. Specific guidelines have been developed to facilitate the development of such systems [ASTM, 1993].

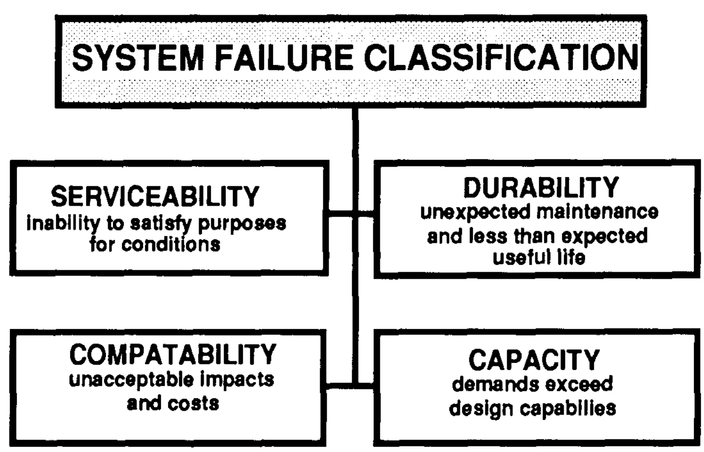

Figure 6.15 - Classification of system errors

Figure 6.15 summarizes a classification system for system or hardware related errors. These errors range from insufficient capacity and durability to unacceptable serviceability and compatibility.

The issues of system robustness (defect or damage tolerance), design for constructablity, and design for IMR (Inspection, Maintenance, Repair) are criti-

cal aspects of engineering marine structures that will be able to deliver acceptable quality [Bea, 1992; 1993a]. Design of the structure system to assure robustness is intended to combine the beneficial aspects of redundancy, ductility, and excess capacity (it takes all three). The result is a defect and damage tolerant system that is able to maintain its serviceability characteristics in the face of HOE. This has important ramifications with regard to structural design criteria and guidelines. Design for constructability and IMR have similar objectives.

The ISO and other similar guidelines have been developed to primarily address the quality of manufactured systems; to assure that they have acceptable and desirable levels of quality [ISO, 1987; BSI, 1990; Norwegian Standards, 1990].

Figure 6.16 summarizes a classification system for procedure or software errors. These errors can be embedded in engineering design guidelines and computer programs, construction specifications, and operations manuals. With the advent of computers and their integration into many aspects of the design, construction, and operation of marine structures, software errors are of particular concern because "the computer is the ultimate fool." Software errors in which incorrect and inaccurate algorithms were coded into computer programs have been at the root cause of several major failures of marine structures [ISO, 1987]. Guidelines have been developed to address the quality of computer software for the performance of finite element analyses [National Agency for Finite Elements and Standards, 1990]. Software testing has been performed to assure that the software performs as it should and that the documentation is sufficient.

Given the rapid pace at which significant industrial and technical developments have been taking place, there has been a tendency to make design guidelines, construction specifications, and operating manuals more and more complex. In many cases, poor organization and documentation of software and procedures has exacerbated the tendencies for humans to make errors. Simplicity, clarity, completeness, accuracy, and good organization are desirable attributes in procedures developed for the design, construction, and operation of marine structures.

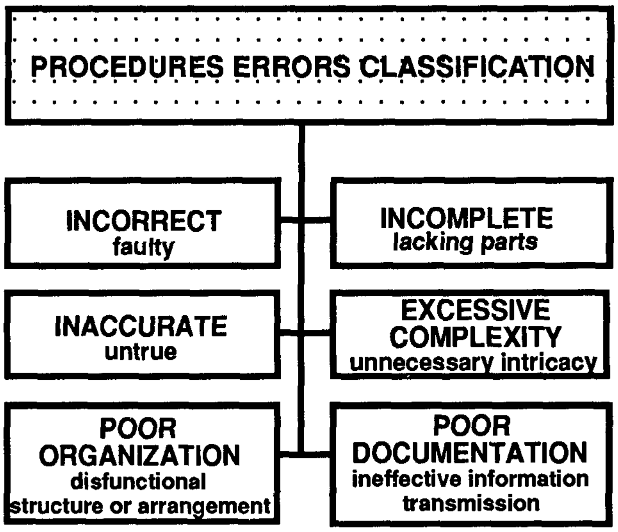

Figure 6.16 - Classification of errors in procedures

Summary

Unsatisfactory quality is defined as undesirable or unanticipated poor performance associated with the structures. The unsatisfactory quality in marine structures results from not only in the catastrophic collapse or loss of the structure (exceed capacity), but as well and perhaps more frequently, results from unexpected durability problems (insufficient corrosion and fatigue cracking resistance).

The causes of unsatisfactory quality can be organized into three categories: 1) those that underlie the actions, 2) the direct initiating actions, and 3) the compounding or propagating actions. Often, the direct initiating actions are identified and the more important underlying and compounding actions ignored.

A detailed study of case histories of insufficient quality in marine structures indicates that while the direct causes of failure can be attributed to the acts of individuals, the dominant contributing and compounding causes are fundamentally "organizational;" erroneous actions by groups of individuals that influence the direct cause of failure and exacerbate or escalate its development through compounded errors. Of the individual errors, the majority of errors are errors of commission; what was performed was erroneous and purposefully executed. Errors of omission or what was performed was not intentional account for a minority of the causes.

High consequence accidents resulting from HOE can be differentiated into those that occur in design, construction and operation phases of the marine system's life cycle. Unacceptable performance of a marine structure can be the result of improper design and construction of the system. Of the three life-cycle phases of a marine structure, the majority of compromises in the quality of the structure occur during the operating phase and can be attributed to errors developed by operating personnel.

Human and organization interrelationships with systems, procedures, and environments (internal, external) can be organized as shown in Figure 6.9. There are error producing potentials within each of the primary sectors including the human operators (designers, constructors, operators), the organizations that influence these operators, the systems themselves (hardware), the documentation that embody the manuals of use or practice for the systems (software), and finally the external and internal environments. In addition to the error producing potentials within each of these sectors, there are error producing potentials at the interfaces of the sectors.

A taxonomy or classification of errors that can develop due to the actions or inactions of individuals (humans), organizations, hardware, and procedures (software) has been provided in this section. This classification has been developed specifically for the purpose of describing and evaluating the effects of human errors in the design and construction of ship structures.

Chapter 7

ALTERNATIVES FOR MANAGEMENT OF HUMAN ERRORS

Alternatives

In most cases, a combination of human, organization, and technical (system, software), modifications can be used to improve the quality level of a ship structure to acceptable and desirable levels. Table 7.1 lists some effective human, organizational, and system improvement factors which can benefit the quality of ship structures.

Table 7.1 - Quality improvement strategies

Human	Organization	System & Software
Selection	Resource allocation	Human tolerances
Training	Communications	Robustness
Licensing	Decision making	Early warning systems
Verification, checking	Process orientation	Reasonable tolerances
Incentives	Integrity	Design for IMR
Planning	Preparation	Simplicity, clarity
Job design Accountability	Accountability Forward looking	Design for con- structability

There are two fundamental approaches to improve the management of HOE to achieve desirable and acceptable quality in ship structures:

1) improve the management of the causes to reduce the incidence of HOE, and

2) improve the management of the consequences to reduce the effects of HOE.

There are three time frames in which one can focus HOE management activities:

1) prevent errors before the activity,

2) detect and correct errors during the activity,

3) reduce the consequences of the errors after the error is committed.

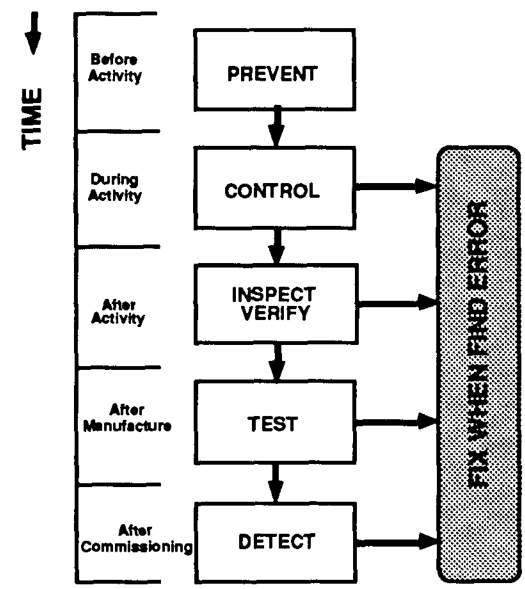

Figure 7.1 - Life-cycle QA / QC efforts

These two approaches and management time frames will be cast in the context of Quality Assurance (QA) and Quality Control (QC) activities. As discussed in Chapter 4 (Figure 7.1), these activities should be continuous processes that are conducted throughout the life-cycle of a ship structure.

As discussed in Chapter 4, experience has amply demonstrated in both marine and non-marine structures that "an ounce of prevention is worth ten tons of cure." The earlier quality problems can be detected and corrected, then the lower the costs and other consequences associated with unanticipated and undesirable low quality. Thus, there is a large premium associated with prevention and avoidance.

Detection and correction (removal, repair) also play vital roles in QA / QC activities. As discussed in Chapter 5, experience has demonstrated that the most effective detection of major HOE is "external" to the situations that cause the HOE. Sufficient resources of experience, knowledge, money, and time and positive incentives for detecting errors are needed if there is to be effective error detection.

It is surprising often how correction is under-estimated. Sufficient provisions are not made for correcting errors when they are found, and the "fixes" become problematic. Detailed thinking and evaluations are necessary to properly define what should be done when major errors are detected. Wishful thinking seems to be behind much of the problems associated with error correction: "it will never happen to me," or "we got by before."

The management of consequences generally also has been under-estimated. In this regard, there is one general rule: there will be HOE. Defenses in depth are required to limit or manage the consequences of this HOE. In the structural design area, design for robustness or damage tolerance has begun to be recognized as an explicit requirement in the structure system. If there is a high probability for a certain type of defect or damage, then it makes sense to provide robustness (combination of redundancy, ductility, and excess capacity) so that there is not a significant degradation in the quality of the structure. It is for this reason that in design for fatigue durability, "fail safe" design is used in many cases rather than "safe life" design.

The life-cycle QA / QC approaches of prevention and management will be discussed in the following parts of this chapter as they apply to the design and construction of ship structures. The concluding section of this chapter suggests responsibilities for improvements in the quality of ship structures.

Team Performance

A particularly important aspect of quality improvement regards "team building." Team-work on the front lines of the design and construction processes can provide a large measure of internal QA / QC during these operations [Huey, Wickens, 1993]. Most important, such team-work can be responsible for interrupting potentially serious and compounding sequences of events that have not been anticipated. It is such teamwork that is largely responsible for "near misses." And, it is for this reason that there are many more near misses than there are accidents.

Crew - team performance has been studied in a variety of different settings [Huey, Wickens, 1993]. These studies have indicated that there are series of key factors that influence crew - team performance. These are summarized in Table 7.2. These factors represent a merging of the primary human and organization management alternatives identified in Table 6.1.

Table 7.2 - Crew - team performance factors

Communications Personnel selection Training Planning Preparations Discipline	Procedures Organization Leadership Monitoring Information seeking, observations	Information evaluation Distributed decision making Appropriate operation strategies Controlling Quality incentives

Variables that affect team performance include rest (fatigue), physical conditioning, boredom, stress, anxiety, fear, training, and design of the hardware and software that comprise the system. Given these variables, it is an important objective to manage the variables so that team performance can be maximized. Provision of sufficient rest, encouragement of good physical conditioning, job design to relieve boredom, reduction of unnecessary stresses and providing for stress relief, removal of unnecessary anxiety and fear, provision of sufficient training and verifying that the training has been absorbed into the work tasks, and design of the hardware and software so that the chances of errors are minimized are examples of team performance variables quality management.

The task difficulty for the team performance is comprised of the goals and performance criteria, the task structure and schedule, the quality and modality of information and communications, the cognitive processing required, and the characteristics of response devices and documentation system. In quality improvement, one important objective is to manage the task difficulty to an optimum level; reducing the task difficulty to the level that will produce the optimum team performance. Clear and non-conflicting goals and performance criteria, simplified task structure, provision of sufficient time to perform the tasks, providing clear, concise, and timely communications, minimizing the cognitive processing required to perform the tasks, and making the response and documentation system as simple and clear as possible are examples of task difficulty quality management strategies.

Design

Figure 7.2 shows a generic design process for a marine structure. The principal phases include concept development, configuration, loading analyses, structural analyses, and design documentation. The individuals working on the design (design team) can make errors which can compromise the intended quality of the design process [Hallas, 1991]. The potential for the errors can be influenced by the organizations, procedures, hardware, and environment that interface with the individuals that perform the design. QA / QC is indicated to be a continuous process through the design to assure that the desirable quality is achieved [ISO, 1994].

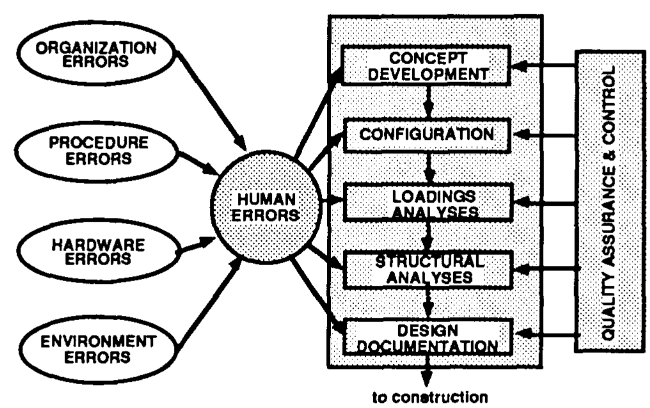

Figure 7.2 - Human factor influences in the design process for a marine structure

Development, documentation and evaluation of advances and improvements made in the engineering technology used to design, construct, and operate ship structures is a main theme of the Ship Structure Committee Research. Reference to the list of SSC reports provides ample evidence of the growth of the technology to design and maintain ship structures.

Recent experience with lack of sufficient quality in ship structures provides ample evidence that it is not the available technology that provides the primary impediments to realizing sufficient quality in ship structures. It is its timely, wise, and correct application [Bea, 1992, 1993a].

Recent experience in which the quality of marine structures have been compromised during the design indicate that there can be errors in any one or all of the principal phases. Generally, it is the unfavorable compounding of more than one major error that can cause such a compromise.

Table 7.3 - Factors influencing the occurrence of design errors

- new or complex design guidelines and specifications
- new or unusual materials
- new or unusual types of loading
- new or unusual types of structures
- new or complex computer programs
- limited qualifications and experience of engineering personnel
- poor organization and management of engineering personnel
- insufficient research, development and testing background
- major extrapolations of past engineering experience
- poor financial climate, initial cost cutting
- poor quality incentives and quality control procedures
- insufficient time, materials, procedures, and hardware

Table 7.3 summarizes some of the key elements that have resulted in major problems that were traceable to design. Design processes that possess a combination of these factors would be those that have a high potential for compromises in the intended quality of the marine structure. It should be a primary objective of QA / QC design measures to first prevent the occurrence of these factors and second to place checks in the primary parts of the design process to verify that they are not developing into an undesirable compromise in the quality of the ship structure.

An example of such development was that associated with the recall of the second generation of Very Large Crude Carriers (VLCC, 240,000 to 260,000 DWT) tankers by Mitsubishi Heavy Industries (MHI) in 1990. This recall was initiated after a large number of major cracks were found in the cargo tanks of one VLCC delivered less than five years earlier. The cracks occurred in the side shell longitudinals, close to the point where they met the transverse bulkheads and frames, about two-thirds up the side. The side shell and longitudinals were made from high tensile steel.

It was related later (Kamoi, 1993) that this development had occurred in the following way. The ship structure was designed by MHI using current classification society rules. Even though they existed and had been highly developed by MHI, first principal methods to compute loadings and structure stresses were not used. Further, there was no explicit design or analysis for fatigue of the ship structure. The ship structure was designed based on the use of conventional mild steel.

After the ship design was completed and documented, it was passed to the yard for construction. The construction yard decided that higher tensile strength steels would be used to reduce the weight of the ship structure in this class of VLCC. This would lower the initial costs, make the yard more competitive, and increase the cargo volumes. Scantlings and plating were reduced in thickness in proportion to the increase in the tensile strength of the steel. The ship structure designers were not consulted about this change.

In the review of the design and construction, the classification society (NK) did not determine that there was anything wrong with the change in the grades of steel. There had not been any significant compromise in the strength or capacity of the ship structure. There were no provisions for verifying that the ship structure had sufficient or desirable durability.

Thus the class of ships were constructed and classed. However, they did not have sufficient durability and very costly measures were required to provide the necessary durability.

This compromise in quality occurred because of a compounding of factors. Not using the available technology, a break down in communications between the design and construction organizations, a contracting and financial climate that did not include a premium for durability, and the inability of the classification society to determine that there would be a significant reduction in the durability with the change in steel grade lead to this costly compromise. There have been other similar problems with other classes of crude carriers.

The effect of a design error depends on the type and magnitude of the error and the sensitivity of the structure element to the error. Figure 7.3 shows the likelihood of unsatisfactory quality in a structure element (Pfs | e) conditional on the magnitude and type of human error. Error tolerant and error intolerant elements are indicated [Stewart, 1990].

It would be desirable that QA / QC be very stringent for the error intolerant elements. Also, it would be desirable to configure or design the element or component so that it could be error tolerant for the highly likely types of design, construction, and / or operations errors. The design of damage or defect tolerant ("robust") structures is very desirable [Bea, 1992]. The sensitivities of various parts of a particular structure and various parts of a particular design process can be studied beforehand to determine those parts that are most error intolerant. Re-design and QA / QC efforts can thus be directed at those elements and aspects that have the highest criticality. These same elements and

components could become those that are watched most closely during the construction and during operations. Inspections can be directed to confirm the quality and condition of the elements that are the most important to the integrity of the ship structure and that are the most intolerant of low quality factors.

Table 7.4 addresses four key questions associated with design QA / QC: "what, when, how, and who to check" [Knoll, 1986]. High consequence of error parts are those aspects of the design process that are error intolerant (Figure 7.3). These are a high priority for QA / QC measures [Stewart, 1990].

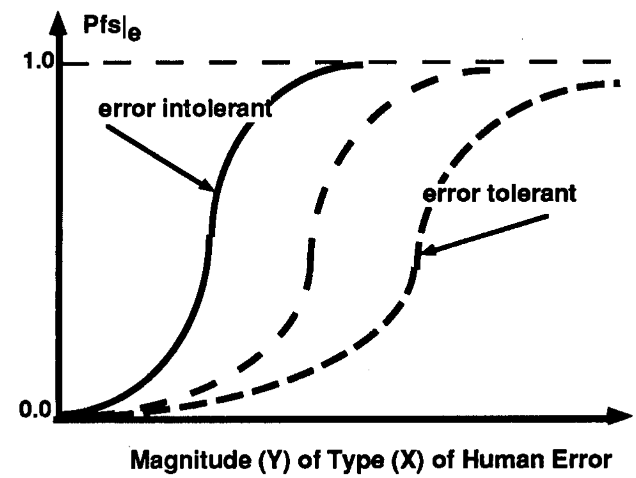

Figure 7.3 - Likelihood of unsatisfactory quality for error tolerant and intolerant structure elements

Early checking is particularly important to identify and correct mistakes that can become embedded in the entire process. As more time is allowed to pass, these embedded mistakes become more and more difficult to detect and expensive to correct. Based on the work published by Knoll [1986], Figure 7.4 shows how insufficient checking in a design process allows the accumulation of errors through the design phase. Announced external audits with effective mechanisms for checking detect these errors so that they can be kept to an acceptable level. The timing of these audits is best scheduled before the design starts (to detect and correct critical flaws in the proposed approaches), during the critical parts of the design (to detect and correct major errors of commission and omission), and after the design documentation has been completed (to detect major errors in the plans and specifications that will be used for construction).

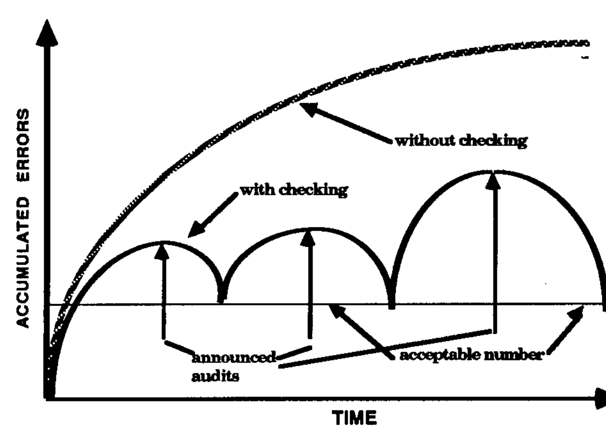

Figure 7.4 - Accumulated errors in the structure design process with and without external checking

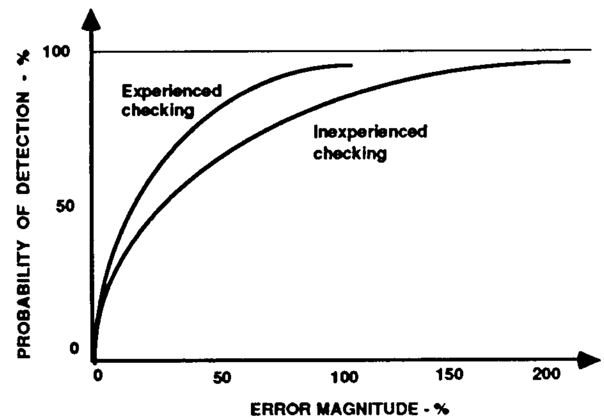

Figure 7.5 - Effects of QA / QC "experience" on the POD of structural analysis errors

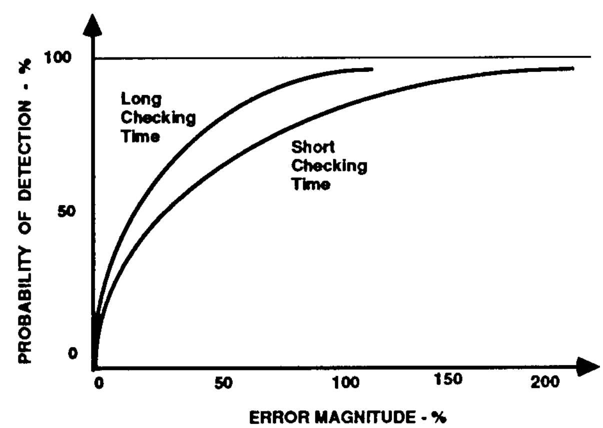

Figure 7.6 - Effects of QA / QC allocated time on the POD of structural analysis errors

The "hows" of checking are particularly important [Knoll, 1986]. The use of qualified and experienced engineers provided with sufficient time and information resources is very important. Figures 7.5 and 7.6 show information that was developed from the research performed by Melchers and Stewart [1980-1990]. These are Probability of Detection (POD) curves developed for errors made in the design of non-marine structures. The error magnitude refers to the size of the error committed in the structural analysis. Positive error magnitudes are indicated (too conservative). Negative error magnitudes would have a different POD curves. Experienced QA / QC is able to detect smaller errors with a higher probability. Provision of more time for checking allows smaller errors to be detected with greater probabilities.

The work of Melchers and Stewart was based on the results of questionnaires directed to building design firms in Australia. These represent the mean results of the responses. This is extremely useful and valuable information. But, it needs to be further developed and directed to the specifics of ship structures before it could be used with surety. Given that there is further development of procedures and processes for the improved management of HOE in the design and construction processes, development of HOE QA / QC alternatives, procedures, and quantified data on the effectiveness of these alternatives and procedures should be a high priority effort.

As discussed in Chapter 6, following the failure of Sleipner A platform, one of the primary changes made in the design process for the replacement platform was a dramatic increase in the resources provided for checking; a 400 % increase [Jakobsen, 1992]. Personnel selection and training was revised. Detailed procedures for the performance of the FEA were developed. Physical testing of critical components was undertaken. And, the error intolerant "star cells" and their reinforcement were modified to develop a more robust structure system [Rettedal, et al., 1993]. All of these measures are excellent exam-

ples of QA / QC in the design process to manage HOE. In the wake of the $ 1 billion disaster, little expense was spared to assure that the replacement platform would not experience the same or similar "embedded flaws" in the structure design process. It didn't.

Table 7.4 - Design QA / QC strategies

• WHAT TO CHECK ? - high likelihood of error parts (e.g. assumptions, loadings, documentation) - high consequence of error parts **• WHEN TO CHECK ?** - before design starts (verify process, qualify team) - during concept development - periodically during remainder of process - after design documentation completed	**• HOW TO CHECK ?** - direct toward the important parts of the structure (error intolerant) - be independent from circumstances which lead to generation of the design - use qualified and experienced engineers - provide sufficient QA / QC resources - assure constructability and IMR **• WHO TO CHECK ?** - the organizations most prone to errors - the design teams most prone to errors - the individuals most prone to errors

Construction

Figure 7.7 shows a generic construction process for a marine structure. The principal phases include contracting, planning, lofting, procurement, cutting and forming, fabrication, and commissioning. The individuals working on the construction (construction team) can make errors which can compromise the intended quality of the design process [Alarcon-Cardenas, 1992]. The potential for the errors can be influenced by the organizations, procedures, hardware, and environment that interface with the individuals that perform the construction. QA / QC is indicated to be a continuous process through the design to assure that the desirable quality is achieved [Al-Bahar, 1988].

The implementation of QA / QC in construction may be summarized by identifying three levels [ISO, 1987]:

1) establishment of QC procedures to monitor quality.

2) establishment of a QA system suitable for the manufactured product in accordance with recognized standards.

3) establishment of a QA system suitable for the manufactured product in accordance with recognized international standards and its certification by an independent certifying authority.

Quality Control Procedures

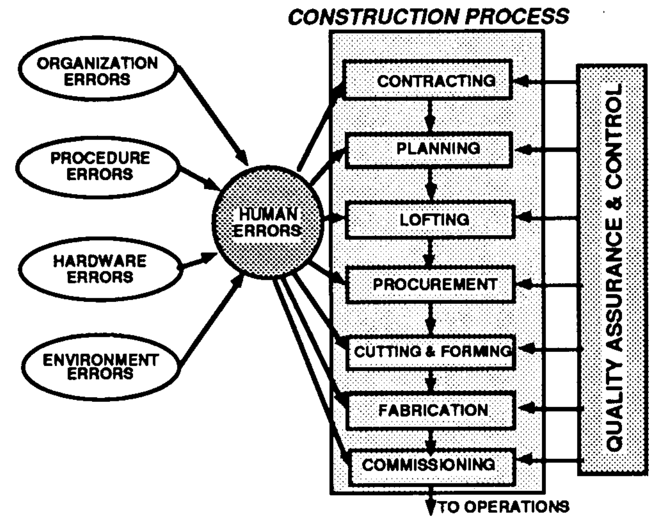

Figure 7.7 - Human factor influences in the construction of a marine structure

The implementation of simple QC procedures to deal with quality requirements is a solution that should not be accepted. Knowledge of the reference quality rules and regulations, a rational organization of the quality staff, the accuracy and completeness of the documents (procedures, plans) produced, and validity of the final records issued are always critical points related to a QC approach.

Knowledge of the technical rules and a basic knowledge of the quality standards may allow constructors to develop workshop quality control plans [Ross, 1984]. This is the average level of capability of small to medium constructors without a specific quality policy.

The appointment of people responsible for the quality of each work area, the issue of a quality manual and related procedures for each discipline involved in the construction (reception of materials, storage, cutting, welding, prefabrication, fabrication, inspections) and the organization of all records for the activities can not be improvised for a constructor not organized according to a comprehensive quality policy.

Quality Assurance Procedures

A correct approach by the yard management to a quality policy in line with recognized standards and therefore the establishment of a QA system is presently the aim of most major constructors of marine structures. It is a mandatory requirement to work on demanding projects. Major requests for tender to yards for a new naval or offshore project are issued today taking into account specific requirements for a QA / QC system.

Safety and reliability of marine structures, highly complex projects, cooperation of many organizations and contractors, involvement of regulatory authorities, very large commercial investments, and tight time schedules justify the implementation of an overall QA / QC system.

Significant evidence and justification of the need for a reliable QA / QC system may be identified by looking at the relationship between cost and time for different project phases. The cost of possible modifications increases on an exponential basis as the project develops, to become prohibitive during the final

offshore installation of a marine structures. On the other hand, the likelihood of the project management being able to deal with the modifications decreases mirror-like during the same phases [Crevani, 1986].

One basic concept of QA / QC is that different quality levels should be defined for the different elements and components comprising a marine structure system depending on the "criticality" of the manufactured item [BSI, 1990; Norwegian Standards, 1990]. If the manufacturing quality of a particular system is particularly sensitive to errors or defects, then increased levels of QA / QC should be directed to that particular system. Lesser levels of QA / QC should be directed to items that are less critical to the quality of a system. Emphasis should be put on the definition of the criticality levels, to properly choose the most adequate QA/ QC scheme for each item to be built.

Three levels of QA requirements have been identified in international standards. These schemes have appeared in the Norwegian standards NS 5801, 2, and 3 [1990], and the same principles were implemented in the subsequent BS 5750, ISO 9001, 9002, and 9003 standards [1990], and the same harmonized European standards EN 29001, 29002, and 29003 [1990].

A synoptic table of comparison of the main requirements of the three quality models for three levels of criticality (most to least) presented in reference [Crevani, 1986] is given in Table 7.5.

Table 7.5 - Comparison of QA / QC construction requirements for different levels of criticality

Requirement	LEVEL* 1	2	3
General requirements	•	**o**	o
Organization	•	**o**	o
Planning	•	**o**	o
Job Instructions and procedures	•	**o**	
Documentation	•	**o**	
Development and design	•		
Subcontracts			
- General	•	**o**	
- Purchasing document	•	•	
- Receiving inspection	•	•	
Identification, marking, storage, shipping	•	**o**	
Measuring and testing	•	**o**	o
Production	•	**o**	o
Inspection	•	**o**	
Records	•	**o**	
Control of non-conformance	•	**o**	o
Corrective action	•	**o**	o
Final inspections	•	**o**	
Quality audit	•	**o**	**o**
	•	**o**	

* Level 1 most critical
• most extensive requirements
o reduced requirements relative to •
o reduced requirements relative to **o**

Certification of compliance with one of the QA / QC schemes requires assessment of the yard's system to be made by a recognized independent authority or third party [ISO, 1987]. The evaluation is to be an accurate on-site examination of the company's quality policy, procedures and records, and their implementation. The major goal of the assessment is to determine whether the QA system complies with the reference standard and is really im-

plemented and permeates all yard departments that may influence the final quality of the product.

Certified companies are systematically audited by the third party to monitor the efficiency of the system, to detect possible non conformities and promote the most appropriate corrective actions aimed at improving the QA structure or QC procedures.

The requirement for certification of an QA / QC system depends basically on regulatory requirements, client requirements, and a strategy of the construction yard to be competitive with the quality of its products.

Inspections, Maintenance, Repairs

Inspection, maintenance, and repairs (IMR) are a critical part of the structural QA / QC process during operations [Bea, 1992]. The IMR process must be in place, working, and being further developed during the entire lifetime of the structure. The IMR process is responsible for maintaining the quality of the structure during the useful lifetime of the structure.

A fundamental and essential part of the IMR process is knowledge. The IMR process can be no more effective or efficient than the knowledge, data, and experience that forms the basis for the process.

The IMR process must be diligent and disciplined and have integrity. There must be a focus on the quality of the performance of the process; quality of the structure will be a natural by-product.

The IMR process should investigate a wide variety of alternatives to accomplish its fundamental objectives (maintenance of strength and serviceability). Inspections can range from general to detailed, visual to acoustic, periodic to continuous (monitoring). Maintenance can range from patching to complete replacement. Repairs can range from replacement as-was to re-design and replacement; temporary to permanent; from complete and comprehensive to judicious neglect.

The IMR process can be proactive (focused on prevention), or it can be reactive (focused on correction). The IMR process can be periodic (time based), or it can be condition oriented (occasion based). Combinations of proactive, reactive, periodic, and condition based approaches can be appropriate for different IMR programs. A major challenge is to find the combination that best fits a particular fleet, its operations, and its organizations.

An IMR process should define the combinations and permutations of IMR that will produce the lowest total costs (initial and future) and optimize the use of resources without compromising minimum safety and reliability requirements.

The fundamental purpose of inspections is to provide information and knowledge concerning the proposed, present, and future integrity of the structure.

The first fundamental purpose of inspections is to "disclose what is not known". The second fundamental purpose is to "confirm what is thought".

Quantitative inspection analyses can help address the second purpose; providing insights into when, where, and how to inspect. Such analyses can not be relied upon to provide information that will address the first purpose.

Inspections, data recording, data archiving (storage), and data analysis should all be a part of a comprehensive and integrated inspection system. Records and thorough understanding of the information contained in these records are a key aspect of inspection programs.

Inspections should be focused on:

- Determination of condition of the structure;
- Disclosure of defects (design, construction, maintenance);
- Assurance of conformance with plans and specifications, guidelines and rules, and quality requirements;
- Disclosure of damage,
- Development of information to improve design, construction, and maintenance procedures.

Inspections should be full-scope and include quality assurance and control measures in the structure, equipment, facilities, and personnel. Definition of the elements to be inspected is based on two principal aspects:

- Consequences of defects and damage, and
- Likelihoods of defects and damage.

The consequence evaluation is essentially focused on defining those elements, and components that have a major influence on the quality of a marine structure. Evaluation of the potential consequences should be based on historical data (experience) and analysis to define the elements that are critical to maintaining the integrity of a marine structure.

The likelihood evaluation is focused on defining those elements that have high Likelihoods of being damaged and defective. Experience and analysis are complementary means of identifying these elements.

Structural monitoring systems can provide important information during operations. These systems can provide intermittent and continuous data on the performance characteristics of the structure. These systems can provide important information to improve design, construction, and operations of marine structures.

There are no general answers to the timing of inspections. The timing of inspections are dependent on:

- The initial and long-term durability characteristics of the structure;
- The margins that the operator wants in place over minimums so that there is sufficient time to plan and implement effective repairs;
- The quality of the inspections and repairs; and
- The basis for maintenance - "on demand" (repair when it "breaks or leaks" or "programmed" (repair or replace on standard time basis).

Marine structures that have been designed and constructed for durability can be expected to have longer periods of time between inspections than those that have not been designed and constructed for durability. Structures that are maintained so as to permit evaluation and planning time in advance of the next IMR will have more frequently scheduled inspections than those that wait until the minimums are reached and then must immediately affect repairs. Structures that are repaired using non-durable methods would implicate more frequent inspections to keep the structure above minimums. Poorly conducted inspections would have similar effects.

The basic objective of structural maintenance is to prevent unwarranted degradation in the strength and serviceability of the structure. Structural maintenance is directed primarily at preventing excessive corrosion through the maintenance of coatings and cathodic protection systems. Another objective of structural maintenance is to preserve the integrity of the structure through judicious renewals of steel and repairs to damaged elements.

The basic tenant of maintenance is that it must be vigilant and continuous if unpleasant surprises in degradation of the structure are to be avoided. Maintenance can be preventative or it can be reactive. Both strategies have their place. For example, preventative maintenance can be directed at corrosion protection of critical structural details (CSD) or fatigue damage to rudder bearings and supports. Reactive maintenance can be directed at repairs to accidental damage and unanticipated fatigue damage to CSD.

Maintenance can be continuous or it can be periodic. In general, for CSD it is periodic and is predicated upon the results of annual or more frequent in-service inspections and special surveys.

Repairs to CSD is a difficult, costly, and demanding task. There is no reasonable consensus on what, how, and when to repair. The general lack of readily retrievable and analyzable information on repairs and maintenance frustrates repair and maintenance tracking. In-service experience is indicating that many repairs do not produce quality results. Development of engineering guidelines to assist in definition of quality repairs to marine structures should be a high priority research and development objective.

Organization Responsibilities

A key consideration in achieving desirable and acceptable quality in the design, construction, and operation of ship structures is organizational. This consideration address how the organizational sectors of the industry can work more effectively toward a common set of quality goals.

Technical "fixes" alone will not result in the desired objectives of quality. The responsibilities and authorities for quality should be clearly understood by all of the primary parties involved in the design, construction, and operation of marine structures.

There are four primary groups involved in the development of quality in marine groups: 1) owners and operators, 2) designers and constructors, 3) classification and inspection groups, and 4) regulatory agencies (Figure 7.4).

Of particular importance in development of quality in design, construction, and operations is agreement between the principal sectors of the goals and responsibilities of each sector. Ideally, the responsibilities for each of the four segments could be organized as follows:

1) Regulatory - responsible for definition and verification of compliance with goals and policies of quality in ship structures.

2) Classification and Inspection- responsible for development of classification rules that will guide and verify design, construction, and operation of quality ship structures that meet regulatory and owner requirements, and to assist with the verification of compliance with the classification rules.

3) Design and Construction - responsible for designing and producing marine structures with appropriate quality.

4) Owners and Operators - responsible for design, maintenance, and operation of high quality marine structures and the economic operation of the structures.

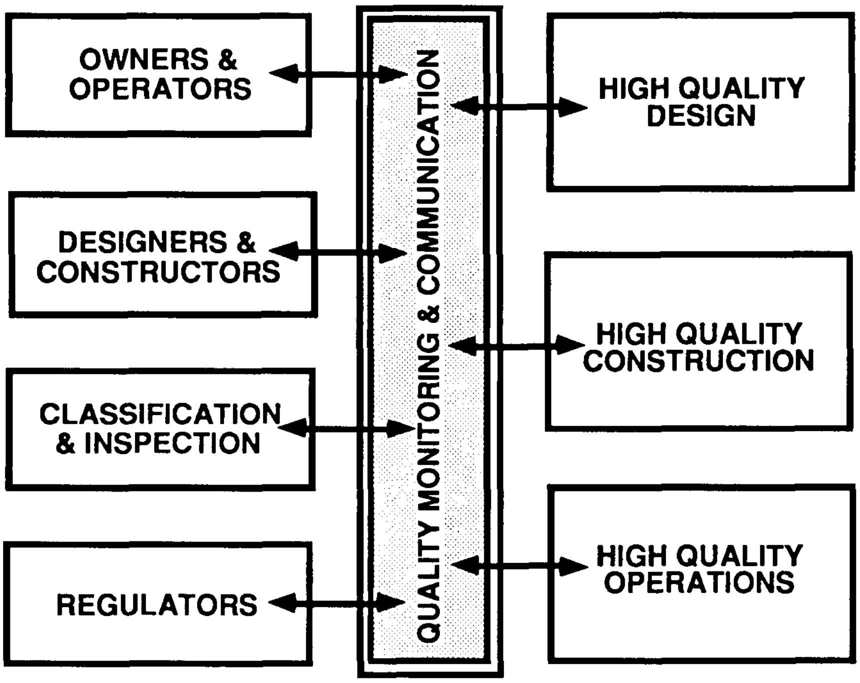

Figure 7.4 - Organizational aspects of quality

The owner and operations segments play a pivotal role in the organization for quality. The owner and operator are substantially responsible for the quality of any ship. They are responsible for establishing the system requirements and objectives and communicating them to the other organizations. The owner / operator is responsible for consideration of the relationships of cost and performance and function.

Table 7.6 summarizes primary organizational and technical responsibilities of each of the groups in development of desirable levels of quality in marine structures.

A very important part of Figure 7.4 is the quality monitoring and communication system shown in the center of the illustration. This system should have three major components that address through the life-cycle of a ship the quality aspects of: 1) operations, 2) structure, and 3) equipment.

Such a system does not exist at the present time. Efforts have been initiated to develop the ship structure components [Schulte-Strathaus, Bea, 1994] and the human - organization components [Mason, Roberts, Bea, 1994] of such a central communications and information database system.

The operations quality aspects would address not only day-to-day mission and cargo operations, but as well human factor related issues through the life-cycle of the ship. The structure and equipment quality aspects would address the life-cycle development of these systems including design, construc-

tion, operation, and maintenance. This would form the information database for managing the life-cycle quality aspects of the ship.

Table 7.6 - Suggested organizational responsibilities for quality in ship structures

SEGMENT	RESPONSIBILITIES
Regulatory	1) Develop and issue technical standards and regulations for QA / QC processes. 2) Perform, evaluate, and report results of design and production reviews and inspections. 3) Perform, evaluate, and report results of operations and maintenance inspections. 4) Archive, review, analyze data, and disseminate information from inspections, repairs, information requests, and field operations reports. 5) Provide information feedback to the responsible Classification, owners - operators, and builders - repair yards. 6) Help develop and recommend marine structure design, inspection, and maintenance improvements.
Classification - Inspection	1) Assist in developing and issuing technical standards and regulations for QA/QC processes. 2)Assist Regulators and Operators in performing, evaluating and reporting the results of design and production reviews and inspections (surveying). 3)Assist Regulators and Operators in performing evaluating, and reporting results of operations and maintenance inspections (surveying). 4) Assist Regulators and Operators in archiving, reviewing, analyzing marine structure quality data, and disseminate information from inspections, repairs, information requests, and field operations reports. 5) Assist Regulators and Operators in providing information feedback to the responsible Classification, owners - operators, and production organizations. 6) Help develop and recommend marine structure design, inspection, and maintenance improvements.

Table 7.6 - Organizational Responsibilities For Quality in Marine Structures (continued)

SEGMENT	RESPONSIBILITIES
Operators - Owners	1) Operate and maintain ships within intended operating conditions. 2) Develop approved standard QA / QC processes including inspection and maintenance programs. 3) Perform continuing inspection and maintenance. 4) Conduct special structural integrity and durability inspections, repairs, and modifications. 5) Review and analyze data from inspections, repairs, information requests, and field service reports. 6) Provide information feedback to the responsible regulatory and production organizations, and other operators. 7) Develop and recommend ship structure design, inspection, and maintenance improvements. 8) Perform continuing liaison with regulatory and manufacturing organizations.
Designers & Constructors	1) Develop and design ships and QA/QC processes to meet or exceed industry, regulatory, and classification society standards and requirements. 2) Produce marine structures that meet or exceed industry, regulatory, and classification society standards and requirements. 3) Recommend preventative maintenance and modification programs. 4) Recommend minimum standard inspections. 5) Recommend special inspections, and modifications. 6) Supply information experience from production, inspections, and maintenance of marine structures 7) Develop design and maintenance improvements. 8) Perform continuing liaison with regulatory and owner/operator organizations. 9) Seek and employ design and operational feed-back

Summary

In most cases, a combination of human, organization, and technical (system, software) modifications can be used to improve the quality level of a ship structure to acceptable and desirable levels. Table 6.1 lists some effective human, organizational, and system improvement factors which can benefit the quality of ship structures.

There are two fundamental approaches to improve the management of HOE to achieve desirable and acceptable quality in ship structures:

1) improve the management of the causes to reduce the incidence of HOE, and

2) improve the management of the consequences to reduce the effects of HOE.

These two approaches will be discussed in the following parts of this chapter as they apply to QA / QC in the design and construction of ship structures. The concluding section of this chapter suggests responsibilities for improvements in the quality of ship structures.

A particularly important aspect of quality improvement regards "team building." Team-work on the front lines of the design and construction processes can provide a large measure of internal QA / QC during these operations. Most important, such team-work can be responsible for interrupting potentially serious and compounding sequences of events that have not been anticipated. It is such teamwork that is largely responsible for "near misses." And, it is for this reason that there are many more near misses than there are accidents.

Recent experience with lack of sufficient quality in ship structures provides ample evidence that it is not the available technology that provides the primary impediments to realizing sufficient quality in ship structures. It is its timely, wise, and correct application [Bea, 1993].

Recent experience in which the quality of marine structures have been compromised during the design indicate that there can be errors in any one or all of the principal phases. Generally, it is the unfavorable compounding of more than one major error that can cause such a compromise. Table 6.2 summarizes some of the key elements that have resulted in major problems that were traceable to design. Design processes that possess a combination of these factors would be those that have a high potential for compromises in the intended quality of the marine structure.

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Table 6.1 summarizes some of the key elements that have resulted in major problems that were traceable to design. Design processes that possess a combination of these factors would be those that have a high potential for compromises in the intended quality of the marine structure. It should be a primary objective of QA / QC design measures to first prevent the occurrence of these factors and second to place checks in the primary parts of the design process to verify that they are not developing into an undesirable compromise in the quality of the ship structure. QA / QC should be continuous throughout the design process.

It would be desirable that QA / QC be very stringent for the error intolerant elements. Also, it would be desirable to configure or design the element or component so that it could be error tolerant for the highly likely types of design, construction, and / or operations errors. The design of damage or defect tolerant ("robust") structures is very desirable. The sensitivities of various parts of a particular structure and various parts of a particular design process can be studied beforehand to determine those parts that are most error intolerant. Re-design and QA / QC efforts can thus be directed at those elements and aspects that have the highest criticality. These same elements and components could become those that are watched most closely during the construction and during operations. Inspections can be directed to confirm the quality and condition of the elements that are the most important to the integrity of the ship structure and that are the most intolerant of low quality factors.

Similar QA / QC procedures have been outlined for the construction of ship structures. The ISO 9000 series has been directed primarily at achieving quality in manufactured products. Qualification under the ISO 9000 series is intended to help bring a measure of uniformity and quality to the construction of marine structures. Background and application of these guidelines have been reviewed in this chapter.

This chapter concludes with a suggestion of responsibilities and accountabilities for quality in the design, construction, and operation of ship structures. The roles of owners / operators, regulatory agencies, classification and inspection agencies, and designers / constructors are suggested.

An important aspect for future development is that of a ship life-cycle quality information and communication system. It will be of critical importance to integrate the human factors issues developed in this chapter into such a database, and in addition the similar human factor considerations that relate to the all important operations phase. The U. S. Coast Guard has initiated efforts in this direction [Sanquist, et al., 1993].

Chapter 8

EVALUATION APPROACHES & QUANTIFICATION

Introduction

The objective of this chapter is to define, outline and discuss approaches to the evaluation and assessment of human error effects on the design and construction of ship structures. The different approaches are intended to allow one to study the physical aspects of systems and procedural - human aspects in their present or proposed form, identify potential improvements and potential *critical flaws*, and identify how best to improve the quality of the systems and procedures.

There are three alternative approaches that can be used to develop evaluations of HOE effects on the quality of ship structures:

1) qualitative,
2) quantitative, and
3) mixed qualitative - quantitative.

It is important to stress that these three approaches are complimentary. They should be used in different stages and parts of the HOE evaluation process.

Qualitative - Subjective

The first approach can be identified as *subjective* or *qualitative* (Figure 8.1). This approach is generally the starting point for the evaluation and assessment processes. In many cases, this approach can prove to be sufficient to achieve and assure the desired level of quality in the ship structure. This approach uses 'soft' linguistic variables to describe systems and procedures. Integration of the evaluations is subjective. This approach may or may not in-

volve detailed structuring of systems and the EDA (Events, Decisions, Actions) that may influence the quality of these systems.

Quantitative - Objective

The second approach can be termed *objective* or *quantitative.* This approach is generally utilized for higher consequence systems and processes in which undesirable levels of quality have potentially severe ramifications. This approach generally examines in much greater detail the systems and the EDA that influence the quality of these systems.

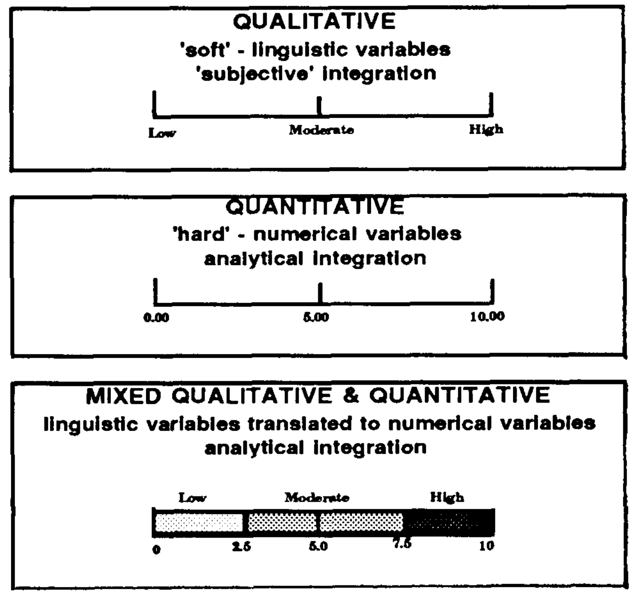


Figure 8.1 - Evaluation approaches

This approach utilizes numerical models to provide quantitative indications of what the effects are of changes in the quality management systems and procedures. This approach generally focuses on the critical aspects of systems that have been evaluated using the more general qualitative methods. This approach uses *hard* numerical variables to describe systems and procedures. The analytical models provide for integration of the effects and variables.

The quantitative approach has traditionally been identified as the PRA (Probabilistic Risk Analysis) or QRA (Quantified Risk Analysis) approach. It has been highly developed and applied to a wide variety of types of engineered systems. It has seen particular development and application in nuclear power plants. However, it has been applied to marine systems such as offshore platforms and pipelines.

Mixed Qualitative - Quantitative

The third approach is a mixed qualitative and quantitative process. Linguistic variables are translated to numerical variables. A mathematical process is provided to perform analytical integration of the effects and variables. In one form, this approach has been based on the mathematics of "Fuzzy Sets" [Zimmermann, 1991]. Moore and Bea (1993b) utilized such an approach in development of HESIM (Human Error Safety Index Method) to assist in the quantitative evaluations of HOE in operations of marine systems (ships, offshore platforms). Gale, et al. (1994) utilized a similar ranking - index method to evaluate the potentials for fires and explosions onboard offshore platforms. This method has been identified as FLAIM (Fire and Life safety

Assessment Indexing Method). The HESIM and FLAIM approaches are summarized in Appendix C.

This approach has been termed "soft computing". The rigid structure of formal probability theory and analytical quantification are surrendered in favor of a "more flexible" structure. Expert systems (knowledge base systems) and neural networks have been combined with the theory of Fuzzy Sets to provide an evolving approach to the evaluation of systems in which there is either no need or it is not desirable to follow the computationally more demanding "hard computing" approaches. This approach is being applied to a wide variety of systems (Brown, et al., 1985). This approach is in a state of development and evolution in a wide variety of marine and non-marine sectors.

Fundamentally this third approach can be developed and applied in the context of the first two approaches discussed here (Moore, Bea, 1993b; Gale, et al., 1994]. The analysts must be willing to surrender rigid interpretations applied to the numerical quantifications and analyses. Conventional probability theory and mathematics can be used to provide the necessary quantifications if one will adopt a "Bayesian" philosophy in which the probabilistic expressions are interpreted to be expressions of the degree of belief [Orisamolu, Bea, 1993].

Indexing methods require calibration to develop results that are consistent with those developed from quantitative PRA or QRA methods. As reliable data is developed, analyzed, and integrated into the evaluations, the degree of subjectivity can be decreased.

Sources of Quantifications

A detailed study of the present databases on marine systems in which there has been unacceptable levels of quality indicates that they are very deficient in their ability to accurately define the key initiating, contributing, and compounding factors that lead to compromises of operating quality.

There has not been any common classification or definition of causes of marine accidents. There has been a dearth of well trained investigators. Investigations generally have focused on the immediate causes of quality problems, not the underlying factors that lead to these causes. Investigations have frequently been focused on placing blame rather than on determining the underlying, direct, and contributing factors. Organizational factors have largely been ignored. Due to legal action concerns, there is not a single generally available database that addresses violations or intentional circumvention related causes of low quality in marine systems.

There is not a single available database that addresses the very important near misses. Inclusion of such information in operating databases could help indicate how design, construction, and operating personnel are able to interrupt potentially catastrophic compounding sequences of problems and

bring the system back to a safe condition. If developed and employed on "real time" basis, such information could provide very important early warnings of developing problems with design, construction, and operating systems.

In all portions of the quality improvement process, data on HOE causes and effects is sadly lacking. There has not been a common vocabulary to describe direct, contributing, and compounding causes. There is little definitive information on the rates and effects of human errors and their interactions with organizations, environments, hardware, and software. There is even less definitive information on how contributing factors influence the rates of human errors.

Given the requirement to improve the quality of marine structures and a need to implement alternative QA / QC strategies in design, construction, and operation of marine structures, there is a pressing need to begin gathering, archiving and analyzing high quality data on HOE incidence, causes, and effects. Some organizations have begun such developments. These efforts need to be encouraged and extended.

Sources of Data

Given the dearth of reliable quantitative information that is presently available on HOE in design and construction of marine systems, the analysts are left with four primary sources of information to perform evaluations:

1) judgment,
2) simulations,
3) field, laboratory, and office experiments, and
4) process reviews, accident and near-miss investigations.

All of these sources represent viable means of providing quantitative evaluations. It is rare to find a structured and consistent use of these four approaches in HOE assessments.

Simulations in the laboratory, office, or field can provide significant insights into how and when errors are developed. The use of simulators is an important way to "train-out" error promoting tendencies. Simulations and simulators can not replicate the stresses and pressures of real situations (recovery is always possible and the consequences are rarely fatal).

Field and office experiments are an important way to gather information on errors. They represent samplings of the more general situation being studied, and must be carefully designed to avoid bias in the results.

Process reviews, accident and near-miss investigations also are an important source of information that if carefully and insightfully done can provide important data on errors in situations in which stresses and pressures are high. Legal and punitive threats often provide significant impediments to

identifying the contributing, initiating, and compounding causes of these errors. Trained investigators are a "must" in performing such investigations. The use of anonymous accident and near-miss reporting systems have been reasonably successful in developing information on accidents and near-misses.

Judgment is perhaps one of the most important sources of quantitative information. Judgment should not be thought of as the opposite of rational thought. *Qualified* judgment is based upon both the accumulation of experience and a mental synthesis of factors which allow the evaluator to assess the situation and produce results. Judgment has a primary and rightful place in making quantitative evaluations because available data is always deficient for the evaluation of a particular situation.

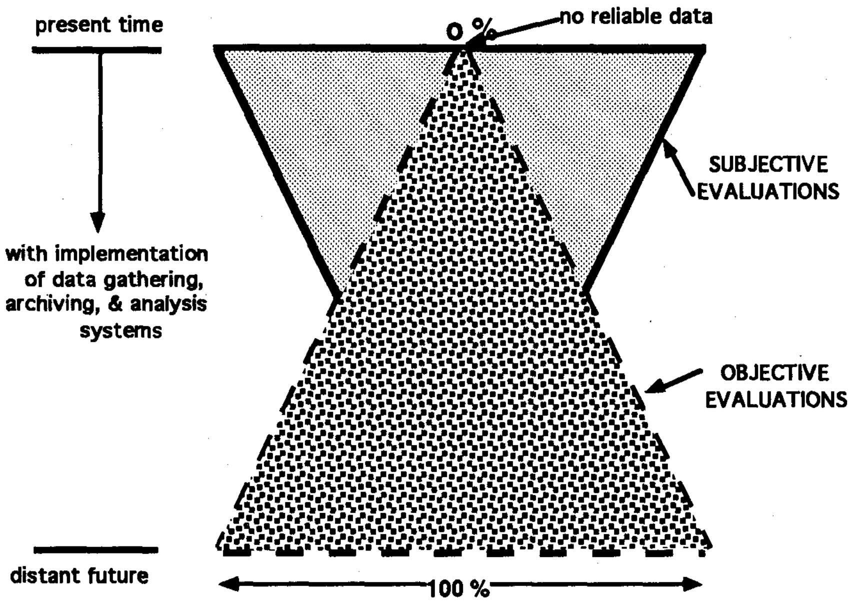


Figure 8.2 - Qualitative & quantitative evaluations

Given the present situation regarding definitive quantitative information on which to base objective quantitative evaluations, one must rely primarily on judgment (Figure 8.2). As adequately structured databases are developed and implemented for HOE evaluations, then in the future, more reliance can be placed on objective data and evaluations based on a combination of data and judgment. It is not likely in the near-term, that sole reliance can be placed on objective data sources to provide quantitative evaluations. Adequately qualified and unbiased judgment will be essential to develop meaningful results.

Judgment can be influenced by a variety of types of "bias" that are identified in Table 8.1. These biases distort the perception of reality. These biases affect the way one interprets the past, predicts the future, and makes choices in the present. These biases or heuristics (rules of thumb) define an evaluator's cognitive structure and dictates the ways things are perceived.

Table 8.1 - Types of judgment bias and its influences

Type of Bias	Influence on Judgment
• Availability	• Probability of easily recalled events are distorted
• Selective perception	• Expectations distort observations of variables relevant to a strategy
• Illusory correlation	• Encourages the belief that unrelated variables are correlated
• Conservatism	• Failure to sufficiently revise forecasts based on new information
• Small samples	• Over estimation of the degree to which small samples are representative of a population
• Wishful thinking	• Probability of desired outcomes judged to be inappropriately high
• Illusion of control	• Over estimation of the personal control over outcomes
• Logical construction	• Logical construction of events which cannot be accurately recalled
• Hindsight	• Over estimation of the predictability of past events

Quantified Data on Task Reliability

Williams [1988], Swain and Guttman [1983], and Edmondson [1993] have published useful summaries that provide quantified information on human errors. This information has been developed primarily for evaluation of HOE effects in the operations of nuclear power plants. The information was developed primarily from experiments and simulations concerning general categories of human task reliability.

Results from the experiments performed by Swain and Guttman [1983] are summarized in Figure 8.3. Generic human error rates are assigned to general types of tasks performed under general types of influences and impediments. The range of error probabilities are intended to be associated with the

potential ranges in the influences and impediments. If the influences and impediments are intense, then the error probabilities will be toward the upper portion of the range and vice versa.

These ranges are intended to define the mean probabilities of a significant or major human error per task performed by the human. The one Standard Deviation ranges associated with generic average rates of human errors have been published by Williams [19888]. The results are summarized in Figure 8.4. The ranges imply general task performance Coefficients of Variation (ratio of Standard Deviation to the Mean) in the range of 50 % to in excess of 100 %.

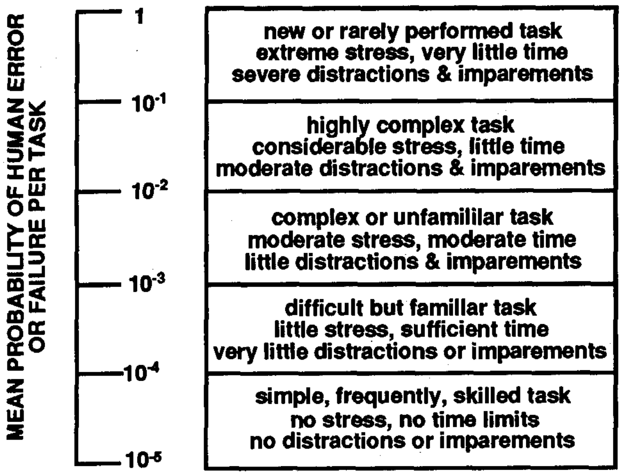


Figure 8.3 - Generic human task error rates

It is important to note that the severity of the error is not captured in any of the available quantitative information. Errors are either major and significant or minor or not significant. It is has been noted that minor or not significant errors are generally caught by the individual or individuals and corrected; hence their lack of importance in the assessment of human reliability [Swain, Guttman, 1988; Dougherty, Frangola, 1988].

Information also has been developed on human error *performance shaping factors* [Williams, 1988; Swain & Guttman, 1983]. These performance shaping factors are influences that can result in an increase in the mean rates of human errors. Simulations, experiments, and information gathered on plant operations provided this information [Dougherty, Frangola, 1988]. The results are summarized in Table 8.2.

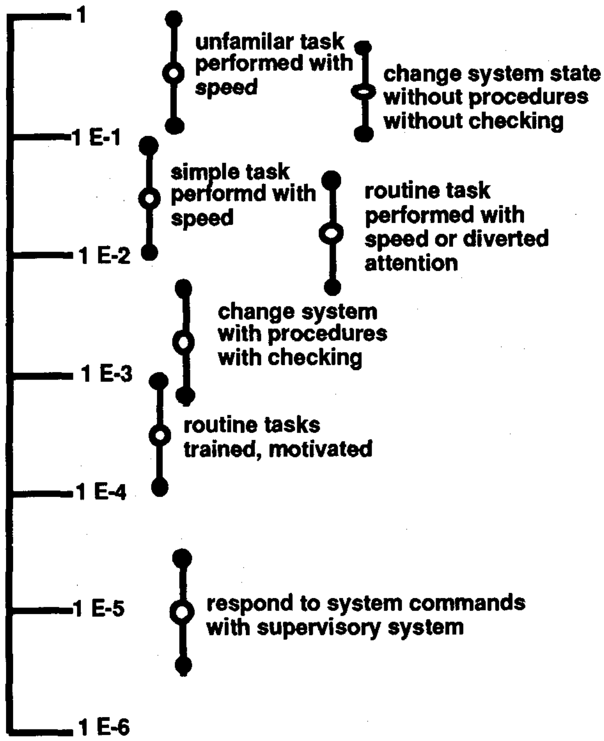


Figure 8.4 - Nominal human task performance unreliability (o - Mean; • - one Standard Deviation)

These performance shaping factors are extremely useful in helping develop quantification of the potential effects of changes in organization, hardware, procedures, and environments on the base rates of human errors.

Information relating to engineering structure design errors have been developed by Melchers and Stewart [1980-1990]. This is the only such information that could be located during this project. Based on surveys of Australian structure design firms, they developed general information on the average of rates of calculation errors and on the average rates of errors associated with different types of engineering analyses or assessments.

This information is summarized in Table 8.3 and Figure 8.5. Structure analysis calculation error rates depend on the number of sequential calculations involved in a given analysis. The calculation error rates are not proportional to the number of calculations. Analyses involving loading combinations and loading reduction factors account for the largest rates of structural design errors. This agrees with the author's personal structural design experience. It certainly indicates where design checking might be most effective at catching major errors.

Table 8.2 - Performance shaping factors

Error Producing Condition	Multiplier
Unfamiliarity	17
Time shortage	11
Low signal to noise ratio	10
Features over-ride allowed	9
Spatial / functional incompatibility	8
Design model mismatch	8
Irreversible action	8
Information overload	6
Technique unlearning	6
Knowledge transfer	5.5
Performance ambiguity	5
Misperception of risk	4
Poor feedback	4
Inexperience	3
Communication filtering	3
Inadequate checking	3
Objectives conflicts	3
Limited diversity	2.5
Educational mismatch	2
Dangerous incentives	2
Lack of exercise	1.8
Unreliable instruments	1.6
Absolute judgments required	1.6
Unclear allocation of functions	1.6
Lack of progress tracking	1.4
Limited physical capabilities	1.4
Emotional stress	1.3
Sleep cycle disruption	1.2

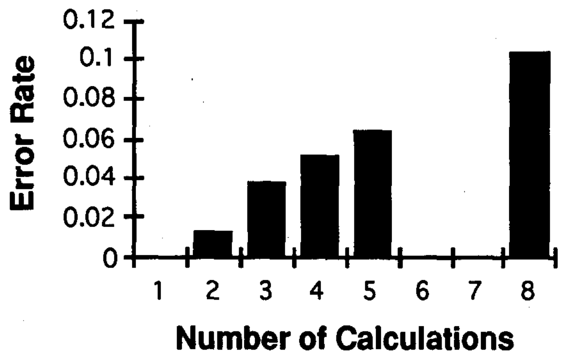


Figure 8.5 - Structural calculations error rates

Table 8.3 - Structural engineering concept error rates

Error	Rate
Code interpretation	0.0150
Ranking	0.0135
Table look-up	0.0126
Loading coefficients	0.1333
Loading directions	0.1000
Reduction factors	0.8000
Loading combinations	0.4167

Analyses of Systems and Procedures

Figure 8.6 outlines a general approach to develop analyses of ship structure design, construction, and operation systems.

Step #1 is to perform an analysis of the system; to define the system hardware, software, the environments (internal, external) in which it must operate, the organizations that can exert important influences on the system, and the individuals (teams, operators) that can interface with the system. This step should result in logical "diagrams" of the physical components of the system.

Step #2 is to perform a process analysis. The process analysis is intended to define how things work; the procedures, premises, and interfaces that can be important to the reliability of the system.

Step #1: PERFORM A SYSTEM ANALYSIS

define system hardware, software, environments, organizations and individuals

Step #2: PERFORM A PROCESS ANALYSIS

define how things are done: how the system hardware, software, environments, organizations, and individuals work

Step #3: PERFORM ANALYSES OF THE SYSTEM & PROCESS AS PRESENTLY CONFIGURED

define the likelihood and "quality" achieved

Step #4: PERFORM ANALYSES OF THE RECONFIGURED SYSTEM & PROCESS

define the likelihood and additional"quality" that could be achieved

Figure 8.6 - Approach to evaluations of systems and procedures

Step #3 is to perform analyses of the system and its processes as it is presently configured. As previously discussed, these analyses can be qualitative, quantitative, and mixed. The objective of these analyses is to provide insights into the levels of quality that can be achieved and into the likelihood of achieving these levels.

Step #4 is to perform analyses of the re-configured system and its processes. A variety of options and alternatives need to be defined. The objective of this step is to understand how effective improvements in the system and processes might be. This step will entail evaluations of the "costs" and "benefits" of these options and alternatives and an assessment of the "best" alternative to achieve the desirable and acceptable level of quality in the system and its processes.

Qualitative Approaches

The qualitative approaches generally focus on general categories of operations performance. General good practice guidelines are given. General rather than detailed studies of the systems are developed. The focus is on performance rather than processes.

In the qualitative approach developed during this project, specific marine systems can be evaluated based on "scales" and attributes developed to reflect the potentials for good or bad operating performance. Figure 8.7 illustrates a qualitative evaluation *instrument* for design of ship structures. Application of the design instrument will be illustrated in the next chapter of this report.

HazOp (Hazard Operability) procedures have been employed in evaluating a wide variety of marine systems. Qualitative approaches have also been identified as Failure Mode and Effect Analysis (FMEA). This approach focuses on both functional analysis and the evaluation of potential consequences. The objective of these analyses is to identify the combination of events that could lead to different degrees of quality and characterize the effects of these different degrees of quality in terms of their potential consequences. The method is structured only in how it is performed. It focuses on a logical analysis of the system and its functions. It does not rely on quantitative or probability based methods.

FMEA attempts to assess the criticality of a component or function of a system on the bias of the minimum number of "failures" in the "failure modes" involving the component or function. If a failure mode (sequence of events leading to low quality) is constituted of one component or function failure, this component or function is indicated to be "criticality #1," and so forth. In this manner, the most critical components and functions in a system are identified. These components and functions then become the primary options for QA / QC measures.

The FMEA approach is relatively simple to understand and apply. It avoids the details and demands of quantitative analyses. FMEA does not generally give a satisfactory indication of priorities because it does not identify the likelihood of occurrence which may differ greatly among components and functions. Also, it fails to account explicitly for couplings and dependencies; common causes and events are not identified. FMEA generally under estimates the true criticality of moderate events or developments of high probability whose combination with several other events or developments of the same time leads to system "failure." Evaluation of past quality problems in design and construction of marine structures indicates that such combinations are generally responsible for "failures."

Yet, with all of these disadvantages, the qualitative methods have much to offer. They should be thought of as providing a framework for thought, debate, analysis, and communication. They should be thought of as providing a complimentary approach to the detailed quantitative approaches.

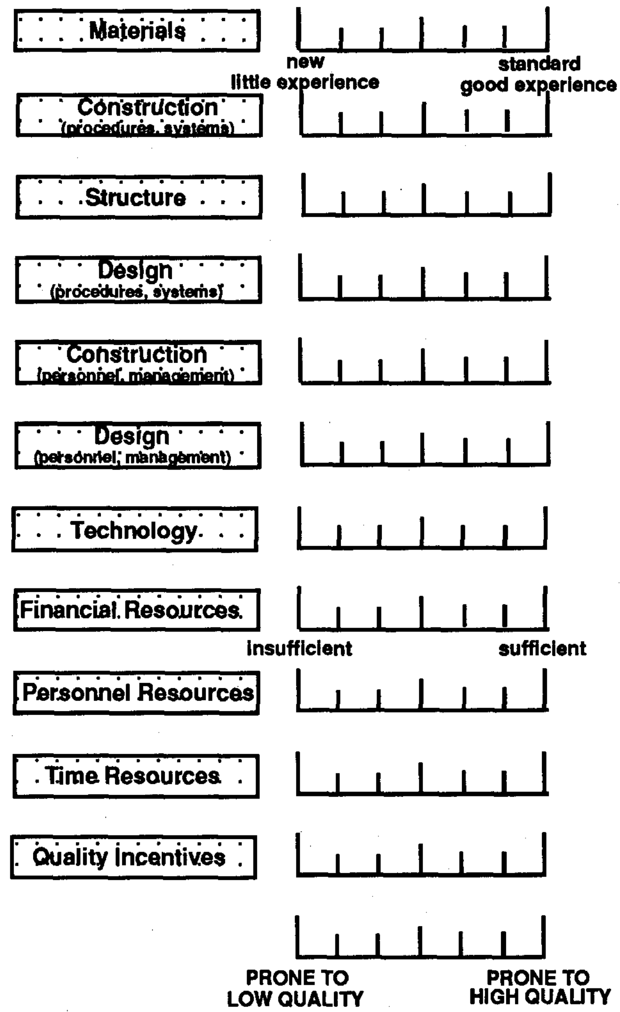


Figure 8.7 - Structure design quality profiling instrument

The qualitative methods can be extremely useful in helping identify important issues and considerations that later, if warranted and useful, can become the primary focus of detailed quantitative approaches. If one attempts to perform detailed quantitative evaluations of all aspects of a system, it quickly gets out of hand; one becomes lost in the *trees* before the *forest* is understood or appreciated.

Quantitative Evaluations

The second approach is oriented to detailing how the operating system works or might not work and quantifying the likelihood associated with performance. This approach is very system specific. Evaluation of the *hardware* and *squishyware* (human, organization, procedure) [Wenk, 1986] aspects also are very specific and detailed. This approach is generally very structured in that probabilistic Event Tree, Fault Tree, and Influence Diagram type analyses are used. Such analyses are frequently identified as Probabilistic Risk Analyses (PRA) or Quantified Risk Analyses (QRA).

PRA / QRA analyses have been used in a wide variety of industrial settings including operations of nuclear power plants, commercial aircraft, liquefied natural gas export and import ports, oil refineries, and offshore platforms. This approach is presently being used in many of the Safety Case studies being performed by platform operators in the U. K. Sector of the North Sea. This approach has been a historic basis of the Norwegian offshore safety management system.

As discussed at the conclusion of the previous section, it is important to realize that the qualitative and quantitative approaches are complimentary. They have the same objective: detecting potentially critical flaws in design, construction, and operations of ship structures, and then defining measures to rectify these critical flaws before acceptable quality is compromised.

The quantitative approach is focused at characterizing the details of how systems are operated while the qualitative approach is focused at characterizing the general performance quality of a system. The results from both of the approaches depend greatly on the individuals that perform the evaluations and the procedures and processes that they utilize. Experience with the particular system and operations should be the primary requirement for those that lead and structure such evaluations.

Strategy for Analyses

It can be desirable to perform quantitative evaluations of marine systems to investigate the need for and effectiveness of quality improvements. A full-scope, life-cycle QA / QC quantitative evaluation should be conducted in "stages" that represent an increasing degree of detail and complexity [Bea, et al., 1992]. These are summarized in Figure 8.8.

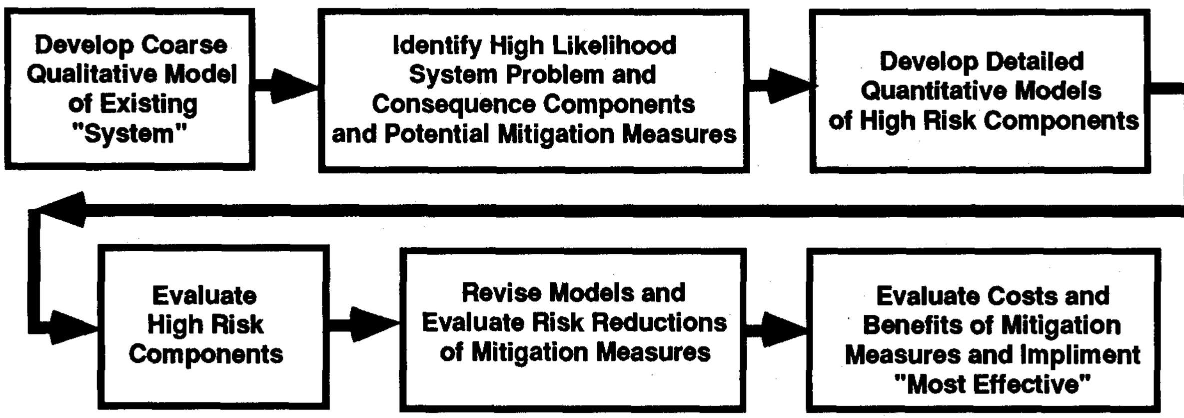


Figure 8.8 - Screening analysis approach to focus on most important aspects

Four stages are suggested that are intended to help progressively "screen" minor from major potential events that can lead to significant compromises in quality of marine structures. These stages are:

1) coarse qualitative,
2) detailed qualitative,
3) coarse quantitative, and
4) detailed quantitative.

The first step in this approach is to detail the physical characteristics of the particular design, construction, and operation "system" that is being evaluated. Next the organizational procedural, hardware, and environments that potentially influence the interfacing of individuals with the system must be detailed.

The next step is to compile a comprehensive list and structure the development of potential life-cycle, full-scope initiating events based on a particular structure and non-structure marine system. This step requires detailed information on the proposed system: how it will be designed, constructed, operated, and maintained. This step also requires personnel that are experienced in each of these activities. Most importantly, experienced personnel with "perverse imaginations" are needed to help perform the analyses of what and how things can go wrong and the consequences. To explicitly address considerations of HOE, the interactions of individuals, organizations, hardware, software, and environments must be interwoven with the physical and procedural aspects of a given marine structure (system).

Many engineers are taught and disciplined to think of how things can and will go right. Experience frequently is the teacher of how things can go wrong and the associated consequences. Throughout the entire process, to provide direction and management of the evaluations and analyses it is much better to have engineers that are experienced in actually performing the marine activities and operations and that are acquainted with reliability analyses

than engineers that are experienced in performing reliability analyses and that are only familiar with marine systems.

The initial qualitative stages (#1 and #2) are very important. These stages not only filter out very important hazards from those that are not so important, but as well result in the basic structuring of the overall assessment process. These stages are most familiar to topsides engineers in that the analyses typically follow the precepts of FMEA. Such studies have been and continue to be used extensively offshore. They have found wide applications in related onshore studies such as those performed for hydrocarbon refineries.

The next step is to define the consequences that are of concern. Based on the definition of quality developed in this report, these consequences fall into four categories: 1) insufficient serviceability, 2) inadequate safety, 3) inadequate durability, and 4) lack of compatibility.

The severity of the consequences can be measured in a variety of ways. For the foregoing categories, for ship structures example measurements include: 1) days of ship unavailability and associated costs due to the ship structure, 2) casualty rate and costs of "failures", 3) fracture rate and costs of repairs, and 4) unanticipated costs, environmental impacts (e.g. in barrels of cargo spilled). Both quantitative scales and associated qualitative scales (e.g. low, moderate, high) can be established to evaluate these consequences. The qualitative scales are calibrated with the quantitative scales so that consistency is maintained in evaluating the consequences.

The importance of initiating events should be judged in terms of their risks. Risks are defined as the product / result of the likelihood of the initiating event and the associated accident path and the consequences associated with the initiating event. Both quantitative and qualitative probability weighted risk scales for each of the categories of consequences should developed and calibrated to produce consistent evaluations.

At the present time, there are several major problems associated with performing quantitative analyses. First, given the present dearth of reliable data on HOE causes and effects, expert judgment must be relied upon to provide the necessary quantifications. Second, there is no generally accepted way to integrate considerations of HOE into the analyses. There are no established procedures and guidelines for the performance of such analyses. Third, performing the quantitative analyses requires a high degree of expertise in how to perform such analyses and a perceptive understanding of the details of the marine system being evaluated. There are few analysts that have such qualifications.

Until these problems can be overcome, the quantitative results should be regarded with caution. It is the process of evaluation and assessment of the details of the system that can provide the greatest benefits to indicate how best to improve the quality of the system. The quantitative analyses should not be allowed to provide *paralysis* in improving the quality of marine structures.

Analytical Approaches

Three techniques can be used to perform quantitative analyses of systems and their functional aspects: Fault Tree Analyses (FTA), Event Tree Analyses (ETA), and Influence Diagram Analyses (IDA) [Orisamolu, Bea, 1993].

Fault Tree Analyses. FTA start with the event of interest (e.g. failure to perform fatigue analyses). Inductive logic of the system and its functions is to determine the causes of the event (e.g. due to organization ?). This approach implies sequential identification of the *unions* (Event A **and** Event B, $A \cap B$) or *intersections* (Event A **or** Event B, $A \cup B$) of events that describe each binary variable down to the point where all inputs are basic events that can not reasonably be analyzed any further.

If two events A and B are *mutually exclusive,* then:

$$P[A \cup B] = P[A] + P[B] \tag{8.1}$$

where P[ ] is the likelihood or probability of the event indicated in the brackets. Mutually exclusive events have no sample points in common. The probability of the unions of a series of mutually exclusive events is equal to the sum of the probabilities of the events.

If two events A and B are *statistically dependent*:

$$P[A \cup B] = P[A] + P[B] - P[A \cap B] \tag{8.2}$$

The probability of B given that A has occurred is termed the *conditional probability* of B given A and is denoted $P[B \mid A]$. It can be defined as:

$$P[B \mid A] = P[A \cap B] \setminus P[A] \tag{8.3}$$

or:

$$P[A \mid B] = P[A \cap B] \setminus P[B] \tag{8.4}$$

The event B is said to be *independent* of A if:

$$P[B \mid A] = P[B] \tag{8.5}$$

Thus for two independent events, A and B:

$$P[A \cap B] = P[A]\, P[B] \tag{8.6}$$

The *occurrence* of the event A does not influence the *probability* of the event B. The intersection of a series of independent events is equal to the product of the individual probabilities.

If A and B are not mutually exclusive, then:

$$P[A \cap B] = P[A \mid B]\, P[B] = P[B \mid A]\, P[A] \tag{8.7}$$

With these basic relationships, one can perform FTA. These same relationships will be those that are used to perform ETA.

FTA can be organized into the four major parts that are described in the following paragraphs.

Part 1 - develop system and functional block diagrams. These diagrams identify the different parts of the system (hardware) and functions (*squishyware*). Their position on the physical - functional paths are described as being in series or parallel (Figure 8.9). The elements that appear in series must all function for the system to function. The failure of any element in series constitutes loss of function or "failure."

The elements that are in parallel operate as redundant elements. One of them must function for the system to function. The failure of one of the parallel elements does not constitute failure of the component formed by the two parallel elements. Both must fail for the component formed by the two parallel elements to fail.

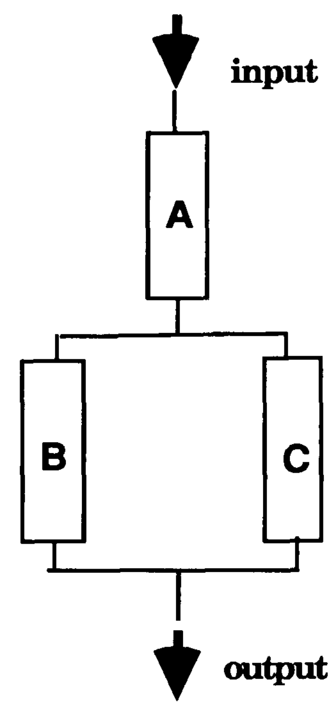


Figure 8.9 - System / functional block diagram

Part 2 - develop the fault trees. Starting from the top failure event of interest, the tree is constituted of a sequence of *gates* representing the logical unions and intersections of events that can lead to the top failure event (Figure 8.10). The variable located just above a gate is equal to the logical function of all variables located below the gate. This requires that those events that are necessary and sufficient to cause the output event appear as inputs to the corresponding gate.

Part 3 - evaluate the probability of the top failure event. The probability of the top event (P[F]) is based on the theory for the probability of unions and the expansion of joint probabilities as products of conditional and marginal probabilities. For the example shown in Figure 8.9, this probability is:

$$P[F] = P[A \cup (B \cap C)] \tag{8.8}$$

$$P[F] = P[A] + P[B \cap C)] - P[A \cap B \cap C)] \quad (8.9)$$

$$P[F] = P[A] + P[B]\, P[C \mid B] - P[A]\, P[B \mid A]\, P[C \mid B] \quad (8.10)$$

If the joint probability of A, B, and C is small enough compared with the probability of the individual failure paths, this expression can be simplified to:

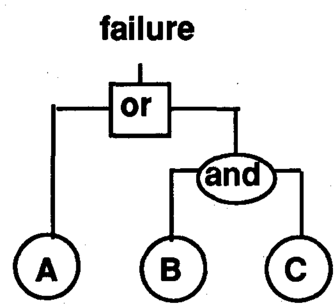
$$P[F] \approx P[A] + P[B] + P[C \mid B] \quad (8.11)$$

If C and B are independent events, then:

$$P[F] \approx P[A] + P[B] + P[C] \quad (8.12)$$

Part 4 - determine the effects of the intensity of "external" events that represent input to the system. The external event or input to the system is denoted as 'E' and its intensity denoted as 'e'. Based on the total probability theorem:

$$P[F] = \Sigma\, P[E=e]\, P[F \mid E=e] \quad (8.13)$$



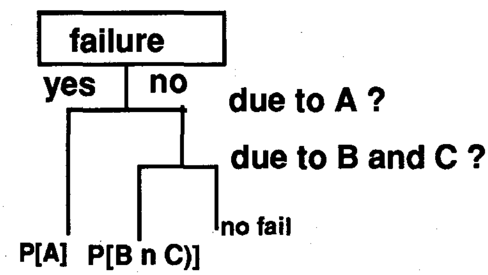


Figure 8.10 - Fault Tree representations of system in Figure 8.9

This approach is known as the *fragility* approach to determining the likelihood of the failure event (P[F]). A fragility curve (Figure 8.11) represents the likelihood of failure given that an event or effect has a given intensity or magnitude (P[F | E=e]). Such curves can be developed from experiments on elements or from analyses of these elements.

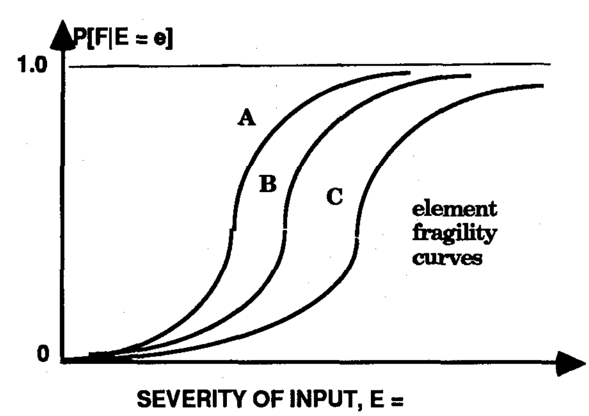


Figure 8.11 - Fragility curves for elements in system shown in Figure 8.9

Hazard or exposure analyses defines the likelihood associated with the occurrence of different intensities of the event or effect of interest (P[E=e]).

In the example developed here, the probability of system failure conditional on E=e can be developed as:

$$P[F \mid E{=}e] = P[A \mid E{=}e] + P[B \mid E{=}e]\, P[C \mid B \cap E{=}e] - P[A \mid E{=}e]\, P[B \mid A \cap E{=}e]\, P[E \mid A \cap B \cap E{=}e] \quad (8.14)$$

In many cases, the last term can be neglected. However, the potential coupling provided by E among the component failures may increase $P[E \mid A \cap B \cap E{=}e]$. This must be determined uniquely for each system and the external events of interest. Again, approximately:

$$P[F \mid E{=}e] \approx P[A \mid E{=}e] + P[B \mid E{=}e] + P[C \mid E{=}e] \quad (8.15)$$

Event Tree Analyses. Event Trees are the conceptual reverse of Fault Trees. Event and Fault Trees frequently are used in combination in performing a PRA or QRA. Event Trees proceed through the same four steps outlined for FTA.

Figure 8.12 shows an Event Tree for the system identified in Figure 8.9.

Event trees are initiated with an event that is important to the quality of the system. This is the *trunk* of the tree.

A sequence of events are then examined to determine how failure might occur. These subsequent events are frequently posed in the form of questions. An Event Tree is formed of an ordered sequence of events that can lead to an outcome of interest. Deductive logic is used to form Event Trees.

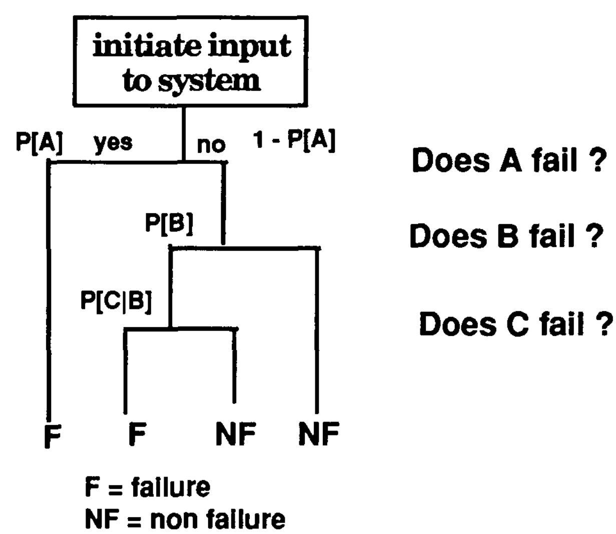


Figure 8.12 - Event Tree representation of system shown in Figure 8.7

An initiating event is identified followed by a definition of the possible sequences of following events. Each branching point in the Event Tree is termed a node. Each event at a given node must be represented by a mutually exclusive, collectively exhaustive set of values or outcomes (e.g. outcome = yes or no in answer to the question posed). There can be any number of branches at a given node as long as they are mutually exclusive (do not have overlapping sample spaces) and exhaustive (their probabilities sum to unity).

Each node is followed by *branches* that represent the possible outcomes. The probabilities attached to these branches define the outcome likelihood distribution conditional on the values of the previous random variables in the tree.

Recognition of the conditional nature of the probabilities in the tree structure is a critical consideration.

The end point or *leaf* of the Event Tree defines the outcome of the sequence of events.

The sum of the failure leaves of the Event Tree shown in Figure 8.12 define the probability of failure of the system:

$$P[F] = P[A] + (1-P[A])\, P[B]\, P[C \mid B] \tag{8.16}$$

$$P[F] = P[A] + P[B]\, P[C \mid B] - P[A]\, P[B]\, P[C \mid B] \tag{8.17}$$

Assuming independence of the events A, B, C:

$$P[F] \approx P[A] + P[B] + P[C] \tag{8.18}$$

These are the same results developed earlier for the FTA of the system in Figure 8.9. Given that there is an intensity or magnitude associated with initiation of input to the system, then this can be handled in the same manner as outlined for the FTA.

Influence Diagram Analyses. Influence Diagrams are equivalent to Event and Fault Trees. They use a different graphical representation. An Influence Diagram is represented by a graphical portrayal of nodes that represent relevant decisions, actions, and influences that determine an outcome that is of interest.

The components of an Influence Diagram (Figure 8.13) are: (1) *decision* and *chance nodes*, (2) *arrows*, (3) *deterministic nodes*, and (4) *value nodes* [Howard, 1990].

Decisions are represented by square nodes which can be a continuous or discrete variable or a set of decision alternatives. Uncertain events or variables are represented by circular or oval chance nodes. Chance nodes can be continuous or discrete random variables or a set of events.

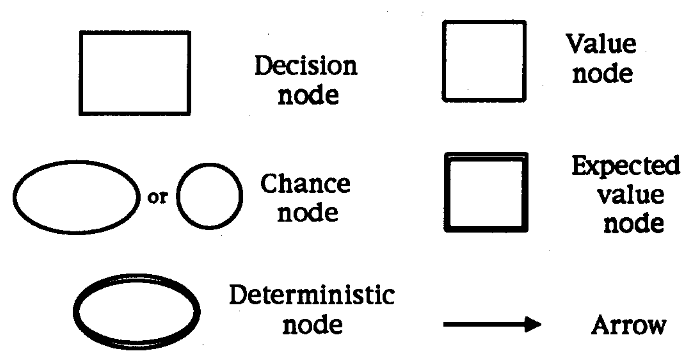


Figure 8.13 - Components that comprise Influence Diagrams

Arrows indicate relationships between nodes in the diagram. Arrows entering a chance node signify that the probability assignments of the node are conditional upon the node from which the arrow originated.

Deterministic nodes are those in which outcomes depend deterministically upon its predecessors. A value node is "the quantity whose certain equivalent is to be optimized by the decisions" of which only one node may be designated in the diagram. Value nodes may be a distribution of possible values. This is represented by a rounded edge single-border node. The value node may also be represented as the expected value. These nodes are represented by a rounded edge double-border rectangle.

Each node corresponds to a file that describes the values of the corresponding variables or event sets and their conditional probability distributions.

Figure 8.14 shows an IDA of the system in Figure 8.9. Reduction of the probability nodes would be accomplished as follows:

$$P[F] = P[A] + P[B]\, P[C \mid B] - P[A]\, P[B \mid A]\, P[C \mid B] \quad (8.19)$$

The evaluation of the probabilities (P[E] and intensities (E=e) associated with the input or initiating demand in Figure 8.11 could be analyzed as follows:

$$P[F] = \sum P[E=e]\, P[F \mid E=e] \quad (8.20)$$

Again, this is directly equivalent to the results developed for the FTA and ETA of the same system.

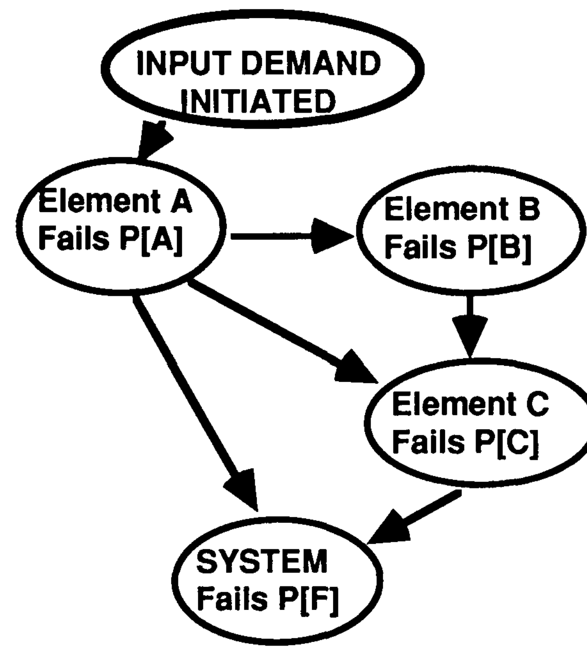


Figure 8.15 - Influence Diagram representation of system in Figure 8.9

Pros and Cons of FTA, ETA, and IDA

FTA portray a static picture of a system and its functions. Time effects or sequences are not captured. FTA do not easily treat continuous systems and the propagation of failures in such systems. They are better suited to binary states (failure, no failure). They do not easily account for partial failure states. FTA are best used to identify potential failure modes and to evaluate if a conjunction of events can lead to system failure.

ETA can include continuous variables and notions of time. The events in an ETA can be ordered in any convenient way provided that the conditionally between the nodes / branches is respected in the evaluations. ETA are not

able to capture easily a functional analysis. At the end of an ETA scenario, the implications of that scenario may need to be determined by a FTA or some other technique.

IDA is a type of probabilistic modeling which allows great flexibility in examining HOE and HOE management alternatives. There are some distinct advantages for using influence diagrams as an alternative to FTA and ETA. It is not necessary for all nodes to be ordered in an IDA. This flexibility allows for decision makers who agree on common based states of information, but differ in ability to observe certain variables in the diagram modeling [Howard, Matheson, 1981]. IDA are able to organize conditional probability assessments required to determine unconditional probabilities of failures of specified target events.

It is to be emphasized that FTA, ETA, and IDA are complimentary. They can be used for different purposes, to develop different details, for to illustrate or evaluate different ways of thinking. The author has found many that do not easily think in FTA terms, yet think easily in ETA terms. Many find IDA confusing and complex. The approach used should match the specific problem, the users, and the objective of the analyses.

Analysis Software

Some excellent computer software is now available to perform FTA, ETA, and IDA. Codes that have been used by the author include InDia [Decision Focus Inc., 1994], @Risk [Palisade Corp., 1994a], and DATA [Palisade Corp., 1994b], and DPL (Decision Programming Language) [Palisade Corp., 1994c]

InDia is a Personal Computer (PC) based program designed specifically to perform IDA. There is a very convenient graphical interface to construct the Influence Diagrams and provide the associated descriptions of the variables and their probabilities. Portions of the IDA can be evaluated. Sensitivity analyses are easily performed to determine the effects of changes in critical variables and dependencies.

@Risk is designed for a variety of types of probability analyses based on Excel spreadsheets for both PC and Macintosh (Mac) computers. Monte Carlo analyses can be performed to evaluate the probabilities in any spreadsheet model. Graphical interfaces are highly developed DPL is very similar to InDia, however, it also can perform ETA and FTA. DATA is designed for both PC and Mac platforms, and is designed specifically to allow evaluations of Decision Trees (FTA, ETA). The trees are structured graphically. The probabilities of event are input in the tree graphical format. Output graphics are excellent.

As with any tool, the quality of the analyses and the use of the associated computer codes lies with the user. The trees or event analyses must be built

correctly; they must capture the essence of the system and the functions. The event sequences and potential failure scenarios must be properly identified and structured. The quantitative input characterizations must be reasonable. Elegant simplicity instead of unnecessary complexity is to be encouraged so that the input, process, and output can be understood by a variety of individuals concerned with improving quality in design and construction of ship structure.

Summary

This chapter has outlined three approaches to developing evaluations of HOE effects on the quality of ship structures:

1) qualitative (subjective evaluations),
2) quantitative (objective evaluations), and
3) mixed qualitative - quantitative (rule - rating evaluations).

Appendix C summarizes two approaches to develop the third type of evaluation. Given the dearth of reliable and detailed data to perform quantitative evaluations, the third type of approach holds much promise for application in ship design and construction HOE evaluations. The mixed qualitative - quantitative approach avoids the majority of the explicit detail and complexity of PRA - QRA quantitative approaches.

These three approaches are complimentary. They should be used at different stages of evaluating a particular system. The qualitative and mixed approaches can be used to *screen* systems to identify the critical or important potential failure modes in a given system. These critical failure modes can then become the focus of the detailed quantitative approach.

Presently available information that can be used to provide quantifications of HOE effects have been summarized. The information is sketchy. Important future efforts should be directed at developing more adequate data on HOE effects in design, construction, and operation of ship structures.

In their best form, application of these approaches can represent uncommon common sense and good management. They are intended to formalize and discipline what high quality, reliability, and productivity individuals and organizations have been developing in the past using other means; generally hard won but often easily forgotten lessons of how to achieve quality in the face of inevitable obstacles.

The quality of what is developed using any of the approaches is directly dependent on the quality of the background and experience of the individuals and procedures that are used to perform the assessments and evaluations. Most important are the incentives, motivations, resources, and rewards provided for those performing the assessments and evaluations. The incentives

need to be directed toward the primary objective: find out how best to improve the reliability and quality of the ship structure.

The motivations behind the evaluations need to be positive: to do the best job possible to define how to achieve quality. A critical motivation should be to empower those on the front lines of the activities that have direct effects on the quality of ship structures.

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Chapter 9

EXAMPLES: QUALITATIVE & QUANTITATIVE ANALYSES

Introduction

The objective of this chapter is to illustrate how the previous developments documented in this report can be used to define measures to improve the quality of ship structures during the design process. The examples are focused on human error control and management during the design process. The fundamental objective of these measures is to assure that a defined level of quality in the ship structure is achieved with a given reliability.

The chapter will first outline generic ship design and construction processes. This outline is intended to provide a representative *template* for illustrating how evaluations of HOE effects might be analyzed and evaluated to improve quality in ship structures.

Generic ship structure design and construction processes are outlined in the first parts of this chapter. These generic design and construction processes can form the general framework for future evaluations of quality management alternatives in design and construction of ship structures.

The generic ship design process is further developed using a quantitative probabilistic approach. This development is used to illustrate the application of the background developed in the previous chapter on the quantitative approach. This development is used in the ship design examples detailed in the last parts of this chapter.

Two examples concerning the design of ship structures will address the activities of the individuals that perform the design (design team), the organizations that influence the performance and activities of the design team, and the procedures used by the design team (design guidelines, classification requirements, software, design procedures). The ergonomic considerations of hardware (e.g. computers) and internal environmental (office lighting, ventilation) aspects will not be addressed in these examples.

The examples address alternatives for improving QA / QC before and during the design process. These alternatives have been outlined in Chapter 7. A quantitative formulation will be developed later in this chapter.

Two non-ship structure examples of quantitative analyses to improve the quality of the structures of offshore platforms have been included in this report. These examples contain many similarities to problems that have been encountered in the design of ship structures.

The first example addresses improved management of HOE in the design of the Sleipner B offshore platform. The analyses in this example were performed by Lt. Robin Noyes as a term project in the course *Reliability Based Design, Construction, and Maintenance Criteria for Marine Structures* [Bea, 1994]. This example examines one specific operation in the design process; the finite element analysis of the platform base "star cell" intersections. The effects of improvements in three critical parts of the analysis process are examined.

As discussed previously in this report, it was a similar design error that caused the failure (sinking) of the Sleipner A platform. This example relies on the use of FTA and ETA to perform the quantitative analyses. This example will be summarized later in this chapter.

The second example addresses the improved management of organization errors in the design of the decks, jackets, and foundations of conventional offshore platforms. This example is based earlier research performed by Professor Paté-Cornell and the author [1989, 1992]. This example examines the generic processes involved in design of the three principal components that comprise platforms (deck, jacket, foundation) and the effects of checking on improving the reliability of the design process. The design phase is analyzed in the context of the construction and operations phases. This example relies on the use of IDA to perform the quantitative analyses. This example is summarized in Appendix D.

Commercial Ship Structure Design and Construction

The commercial ship design and construction process has been studied and documented by the Infrastructure Study in Shipbuilding Project Office, Manufacturing Technology Branch, Manufacturing Systems Division, Systems Department of the David Taylor Research Center in cooperation with the Office of the Associate Administrator for Shipbuilding and Ship Operations, Maritime Administration, U. S. Department of Transportation [Karaszewski, Wade, 1990].

The objective of this study was to undertake an analysis of the U. S. commercial shipbuilding infrastructure as of 1990, with the goal being that of identifying the time-critical functions within the ship acquisition process.

Participants in the study included customer organizations, ship design and systems engineering organizations, classification societies, financial institutions, supply / service vendors and subcontractors, government agencies, labor organizations, and academic / training institutions.

The analysis method utilized in this study was identified as the IDEF (ICAM Definition language). This process is the standard approach used to define manufacturing system requirements in many Department of Defense manufacturing programs and evolved from the Air Force ICAM (Integrated Computer Aided Manufacturing) program. IDEF was used to produce the following three models [Karaszewski, Wade, 1990]:

- *Functional model* - a structured representation of the functions of a system and of the information and objects which interrelate those functions.
- *Information model* - a representation of the structure and semantics of information within the system.
- *Dynamic model* - a representation of the time varying behavior of the process.

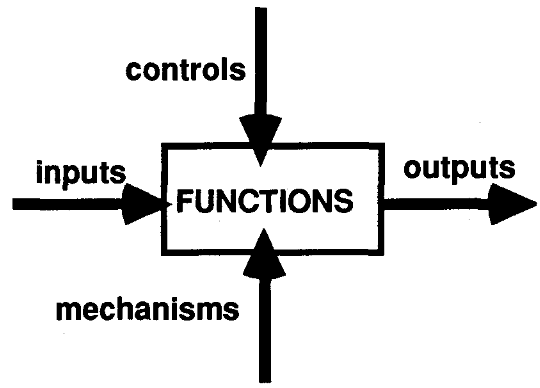

Figure 9.1 - Fundamental IDEF model mechanics

The IDEF mechanics involved definition of the key *Functions (activities)* within the shipbuilding process. Associated with each of the *Functions* were identified *Controls, Inputs, Mechanisms,* and *Outputs* (Figure 9.1).

The IDEF commercial ship design and construction process and the average time required to complete each portion of the process are summarized in Figure 9.2 [Karaszewski, Wade, 1990]. This process is very similar to that defined by Palermo [1986] for U. S. military ships and Glimmer [1975] for U. S. commercial ships.

At the highest level of aggregation, three key IDEF *Functions* were identified:

- *Develop a ship concept* - activities associated market analysis, customer requirements, concept design, and preliminary design.
- *Secure a contract* - development of a contract package, including contract plans and specifications, acquisition of capital financing, and selection of a shipyard.

- *Build and deliver a ship* - detailed design, material procurement, construction, testing, trials, and delivery.

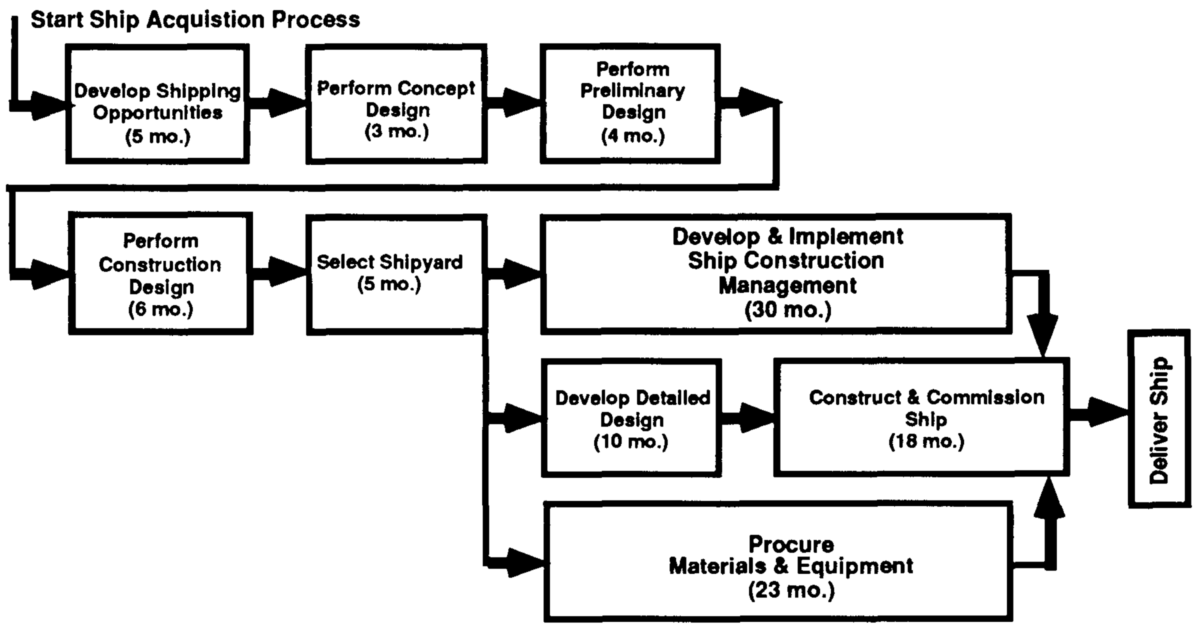

Figure 9.2 - Generic commercial ship design & construction process

Ship Structure Design

The IDEF Functional models for Development of a Ship Concept, Performance of the Concept Design, and Development of a Detailed Design are summarized in Figures 9.3, 9.4, and 9.5, respectively. These models define the key inputs, controls, mechanisms, and outputs associated with each of these models. This provides important information and insight regarding the potential human, organizational, hardware, procedure, and environmental aspects that could influence the quality of the ship structure.

Concept Design

The Concept Design Function (Figure 9.3) is the first step in the design process. The purpose often is to translate a set of operational requirements into the approximate physical characteristics of a ship structure.

The Function constitutes technical feasibility studies to establish the ship characteristics all of which are intended to meet the required space and cargo cubic and deadweight requirements defined by the customer.

Variations in design configuration are generally analyzed in parametric studies during this Function to determine the most economical design solution. The developments during this Function are important because they form the fundamental bases for the subsequent design developments.

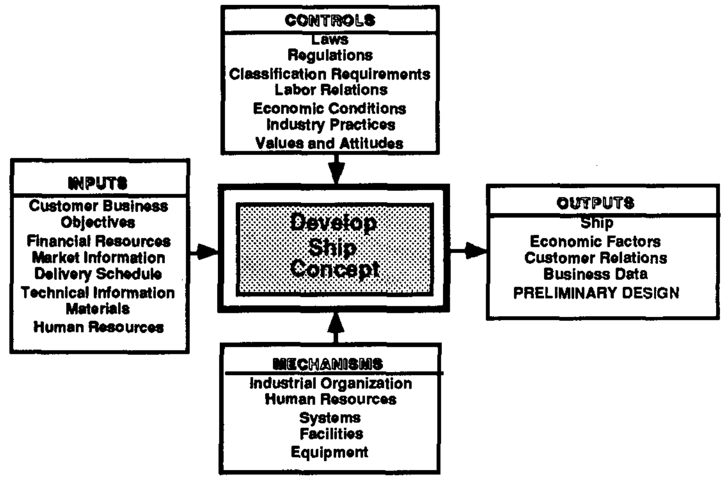

Figure 9.3 - Concept Design Function

Preliminary Design

The Preliminary Design Function (Figure 9.4) involves the development and refinement of the principal characteristics of the ship structure with greater precision that required during the concept design stage. These characteristics include the principal ship dimensions, hull form parameters, and a general arrangement and the hull's structural configuration.

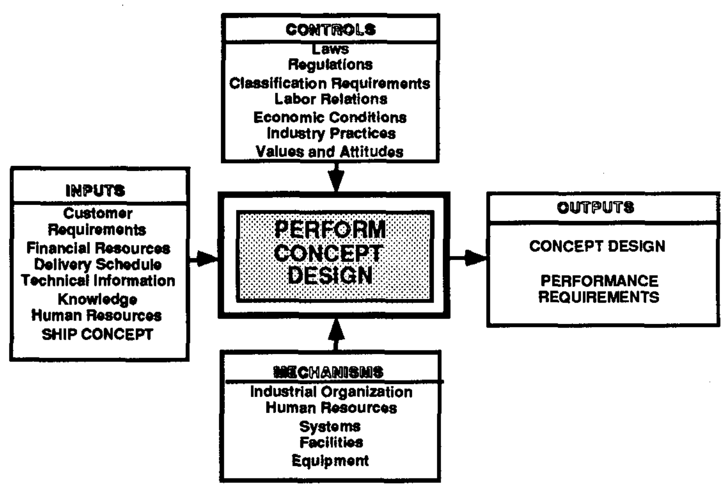

Figure 9.4 - Preliminary Design Function

The entire process is iterative (the *design spiral*) [Taggart, 1980]. The preliminary design package reflects the economic viability of the design as well as the necessary engineering considerations.

The preliminary design process operates under some important constraints that include *industry practice, performance requirements, and the body of rules and classification requirements (laws and regulations).* Key inputs to the preliminary design that were defined in the concept design include *customer requirements* (first cost generally being a major requirement to secure the contract) and the *design knowledge base.* This base is comprised of the information and empirical data pertaining to the class of ship design being considered.

Detailed Design

The Detailed Design Function (Figure 9.5) includes the final and most detailed level of the design process. The detailed design is intended to result in the precise definition of the ship configuration, definition of all material requirements and the preparation of manufacturing support information.

The IDEF Detailed Design Function identified five primary categories of activities that comprise the detailed design:

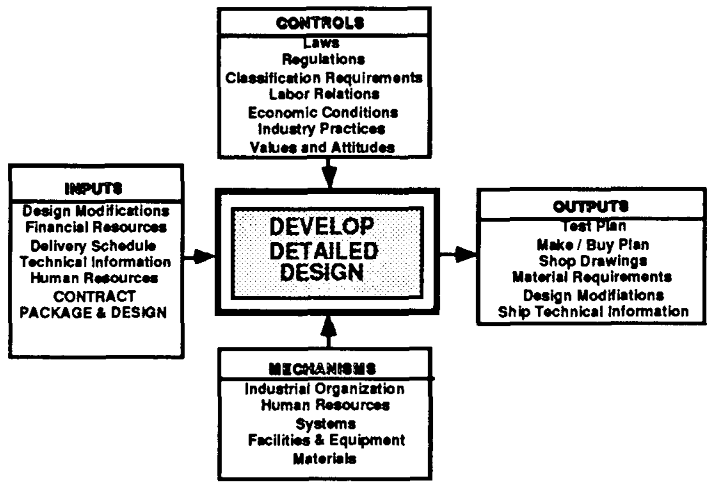

Figure 9.5 - Detailed Design Function

1) Final definition of the ship system - performance requirements, structural characteristics and internal arrangements.

2) Design of the ship systems and components - individual characteristics of all of the structural elements, components (assemblies of elements) and their integration into the ship structure system.

3) Approval of the design - evaluation and approval of the structure system by the owner, classification societies, and regulatory agencies.

4) Development of a production approach - quality standards, hull erection sequence, outfitting plan, and a test plan.

5) Preparation of shop drawings and specifications - all of the written and graphical documentation required to produce the ship.

The principal constraints in the final design Function are the design modifications that develop from the review of the contract and detailed designs by the customer and regulatory bodies, the shipyard allocated resources to the design including production capabilities and design monetary, time, human, testing, and schedule resources.

Design Analyses

Details of the content of the ship structure design process and the associated analyses have been summarized by Hughes [1983], Rawson and Tupper [1983], and Taggart [1980].

A summary of the Detailed Design Process (Figure 9.2) is developed in Figure 9.6. The process is initiated based on the results of the preliminary and construction designs (Figure 9.2). The process consists of four primary *Functions*::

1) *Structure Configuration,*
2) *Structure Loadings Analyses,*
3) *Structure Analyses, and*
4) *Design Documentation*

Specific types of detailed design activities and analyses are identified in Figure 9.6. It is these detailed design activities that can become the activities that are evaluated to determine their HOE implications and how sufficient quality might best be assured.

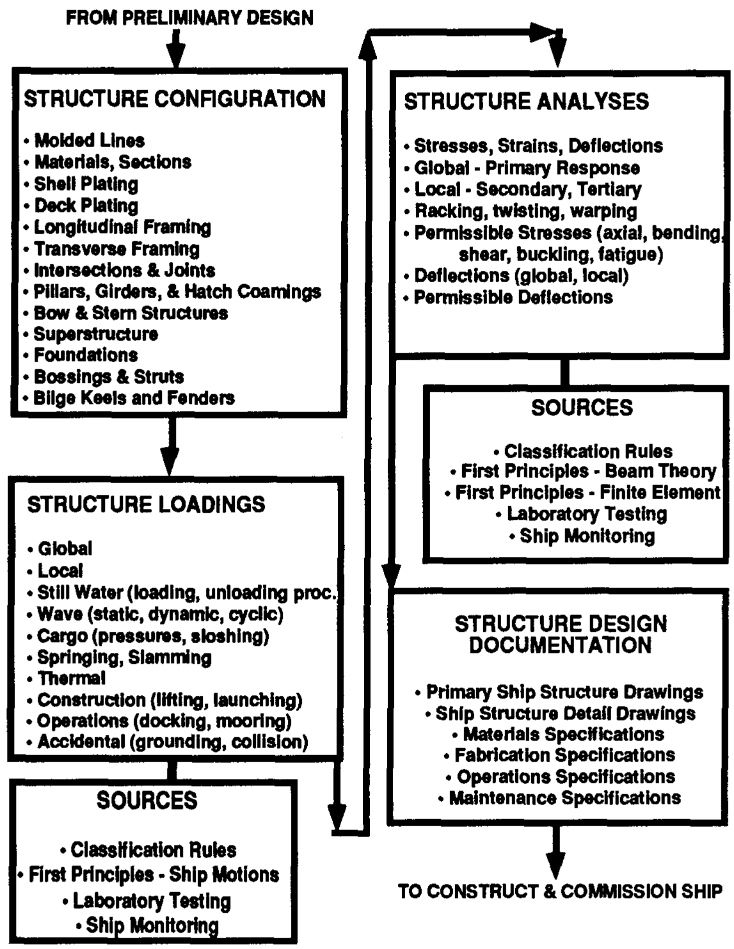

Figure 9.6 - Generic ship structure detailed design process

The principal sources of information that can be utilized in performing the Structure Loadings Analyses and Structure Analyses are identified in Figure 9.6. In a subsequent section of this chapter, this generic detailed design process will be the basis for illustration of the probabilistic analytical approach developments of the previous chapter.

Ship Structure Construction

The third major group of IDEF activities concerns the processes whereby a shipyard and its suppliers and subcontractors construct and deliver a ship; Build and Deliver a Ship. This Function is summarized in Figure 9.7.

In contrast with the preceding activities, the shipyard is primarily on control of this stage of the ship building process. The IDEF model for construction and delivery of a ship identified four major activities:

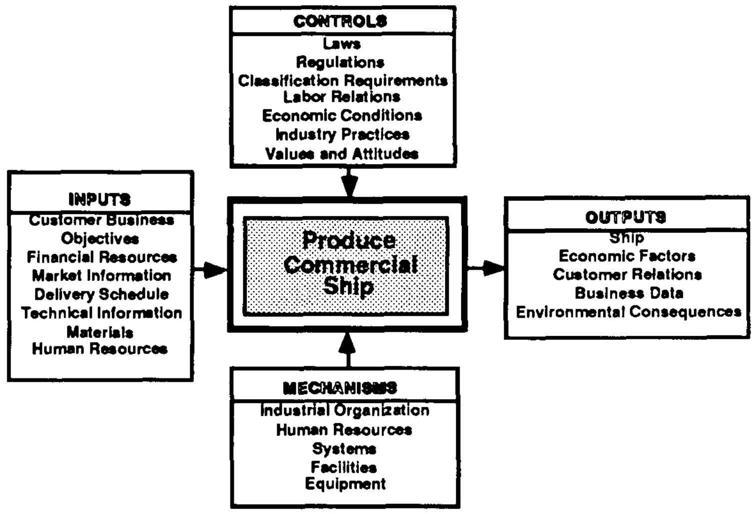

Figure 9.7 - Build and deliver ship function

1) management of the shipyard operation,

2) preparation of a detailed design,

3) procurement of all materia and equipment that will be consumed in building or installed on the ship, and

4) fabrication, assembly and testing of the completed ship.

The study identified an important activity that was missing from the commercial shipbuilding process. This activity involved development of a technical information package that could be delivered to the customer with this ship. This *owner and operators manual* would embody all of the ship operation and maintenance that should be in the hands of the owner and operator. This would be assembled from a variety of sources throughout the entire production process. This ship design and construction database could form the foundation for the development of a *Marine Structural Integrity Program* for the ship throughout its life [Bea, 1993].

The primary inputs to this Function include the contract package, the preliminary production plan, and the human and financial resources plans. The primary outputs include the allocated resources to build the ship, the budgets, schedules and procedures, the customer relations plan, and the business data the monitors the overall cost and schedule performance of the shipyard in relation to the ship construction contract.

The primary controls on the ship production include applicable laws and regulations, economic conditions that influence make and buy decisions,

labor relations, and industry - shipyard practices. The primary mechanisms include qualified human resources (for management, design, production and QA / QC activities), systems required to manage the shipyard operations, and the facilities and equipment including all of the hardware required to administer the shipbuilding.

Based on the IDEF shipbuilding study, and the information documented by Taggert [1980], a generic ship structure construction system has been developed. This system is summarized in Figure 9.8. The system identifies five major categories of *primary* activities:

1) planning and scheduling,
2) lofting,
3) steel procurement and storage,
4) steel cutting and forming, and
5) fabrication and erection.

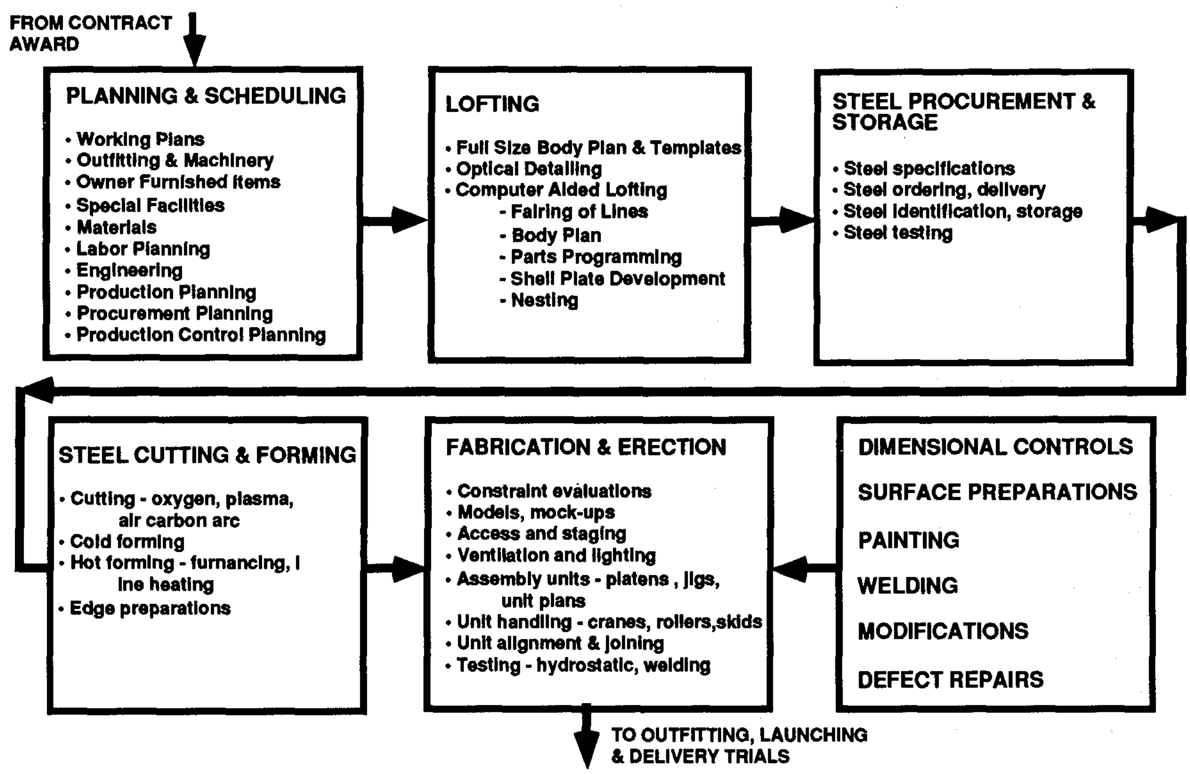

Figure 9.8 - Generic principal activities in construction of ship structures

In addition, the system identifies six *secondary* activities that have direct effects on the fabrication and erection activity. These include dimensional controls, surface preparations, painting, welding, modifications, and defect repairs. Note that the major QA / QC activities are included within the five principal categories of activities.

As for the generic detailed design process developed earlier (Figure 9.6), this generic construction process can be used at the starting point for developing evaluations of construction activities and the HOE effects on these activities.

The developments that follow in this chapter and report will be directed at the ship design process. This was dictated by the defined scope of work for this project. It will be seen that the design process related developments and applications are also applicable to the construction process.

Ship Structure Design Quantitative Formulation

A *system diagram* expression of how HOE can influence the quality of a marine system is illustrated in Figure 9.10. The background for this diagram will be developed based on a quantitative probabilistic approach in this section.

In this development, the human error classifications (individuals, organization, hardware, procedures, systems) that have been developed in this project are assumed to identify sets of mutually exclusive and exhaustive causes.

First Level - Failure to Achieve the Desired Quality

The *System* in Figure 9.10 refers to the ship structure system. The quality of the ship structure system can be directly influenced by two primary categories of factors: 1)*Environments* (E), and 2) *Human Errors* (O).

The category Environments represented by E represent hazards that can result in compromises in the quality of the ship structure that are natural or due to inherent randomness. The category of Human Errors represented by O represent hazards that can result in compromises in the quality of the ship structure that are unnatural or due to human errors.

The ship structure quality attributes are defined as serviceability, safety, durability, and compatibility. These are the four attributes that define the quality of a ship structure. An insufficient quality attribute (i = 1 = serviceability, i = 2 = safety, i = 3 = durability, i = 4 = compatibility) can be caused by *natural causes / inherent randomness (E)* and / or *human error (O).*

The likelihood of insufficient quality in the ship structure is indicated as the probability of failure (Pf_Q). The likelihood of insufficient quality (failure) is the union of the Likelihoods of insufficient serviceability, Pf_1, safety, Pf_2, durability Pf_3, and compatibility Pf_4:

$$Pf_Q = \bigcup Pfi \qquad (i = 1 \text{ to } 4) \qquad (9.1)$$

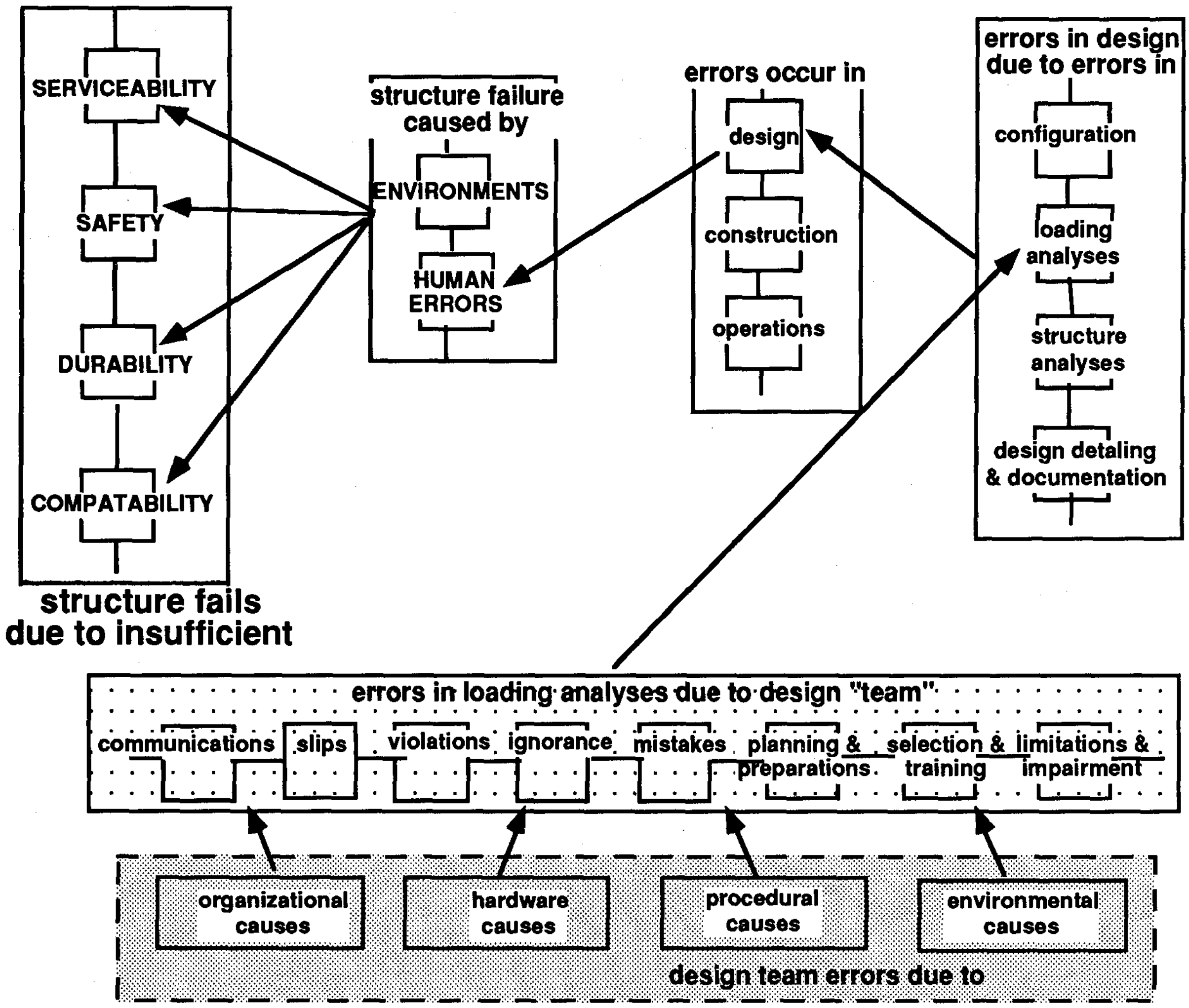

Figure 9.10 - System - procedures analysis incorporating environmental and human error influences

Insufficient Quality - With and Without HOE

The probability of failure of any one of the quality attributes due to inherent randomness will be identified as Pfi_E. The probability of failure of any one of the quality attributes due to human error will be identified as Pfi_O. Then:

$$Pfi = \{Pfi_E \mid O\}\, P[O] + \{Pfi_E \mid \emptyset\}\, P[\emptyset] + Pfi_O\, P[O] \qquad (9.2)$$

where

$$P[\emptyset] = 1 - P[O] = \text{probability of no human error} \qquad (9.3)$$

Life-Cycle Phases of Quality

The likelihood of insufficient quality in the ship structure due to human error could be evaluated in the design (Y_1), construction (Y_2), and operations (Y_3) phases as follows:

$$Pfi_O = \bigcup Pf\,[Yi \mid OY_i]\; P\,[OY_i] \qquad (i = 1 \text{ to } 3) \qquad (9.4)$$

where OY_i indicates a human error that occurs in one of the three life-cycle phases of the ship structure.

Quality in One Phase of the Life Cycle

The likelihood of insufficient quality in the ship structure due to the influences of individuals during the design phase (1.0) could be evaluated as follows:

$$\begin{aligned} Pfi[Y_1 \mid OY_1] = {} & Pfi[Y_{1.1} \mid OY_{1.1}]\; P\,[OY_{1.1}] \cup Pfi[Y_{1.2} \mid OY_{1.2}]\; P\,[OY_{1.2}] \\ & \cup Pfi[Y_{1.3} \mid OY_{1.3}]\; P\,[OY_{1.3}] \cup Pfi[Y_{1.4} \mid OY_{1.4}]\; P\,[OY_{1.4}] \end{aligned} \qquad (9.5)$$

where the subscripts 1.1, 1.2, 1,3, and 1.4 refer to the configuration of the ship structure, the loading analyses, the structure analyses, and the design documentation respectively. These are the four major components that have been identified to form the design activities (Figure 9.6).

Quality in One Part of One Phase of the Life Cycle

The likelihood of insufficient quality in the ship structure due to human error during the loading analyses could be evaluated as follows:

$$Pfi[Y_{1.2}] = \bigcup (Pfi \mid Oj)\; P[Oj \mid Y_{1.2}] \qquad (j = 1 \text{ to } 8) \qquad (9.6)$$

where (Pfi | Oj) refers to the probability of insufficient quality of type i (serviceability, safety, durability, compatibility) of the ship structure due to (conditional upon) a human error of type j. P[Oj] refers to the probability of the human error of type j.

The human error type j subscripts 1 through 8 refer to the individual human error classification system developed in this project. This system is summarized in Figure 9.11. The eight mutually exclusive and exhaustive categories include communications, slips, violations, ignorance, planning and preparation, selection and training, limitations and impairment, and mistakes.

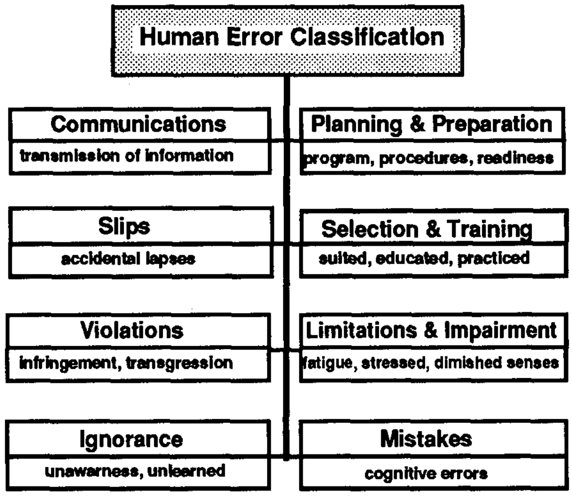

Figure 9.11 - Classification of human errors

(Pfi | Oj) is the "fragility" curve for the hull structure. As discussed previously in this report, this fragility curve could be developed analytically by determining how the particular quality characteristic of the ship hull structure (e.g. its capacity) is influenced by different types and "intensities" of errors.

This explicit evaluation of variable error intensities or magnitudes could be avoided if it were assumed that the errors being addressed were those that resulted in very significant or major degradation in quality. This would be equivalent to defining only two categories of errors: major and minor. It then would be necessary to determine the probability of failure associated with the defined major category of error. Such a definition is consistent with the meager quantitative data that is available on human errors.

It is important to note that the shape of the fragility curve can be changed by engineering. This is design for "robustness" or defect (error) tolerance. For the intensities (magnitude) and types of errors that normally can be expected (for a given QA / QC system), the structure should be configured and designed so that it does not "fail" (or have unacceptable quality) when these types and magnitude of errors occur [Bea, 1992; Das, Garside, 1991].

The likelihood of insufficient quality developing in the other three parts of the design process (configuration, structure analyses, and design documentation) would be developed in a similar manner.

Contributing Influences to Human Errors

The categories of human errors are influenced by four types of contributing influences (error inducing or causing factors): organizations (Oe), hardware (He), procedures (Pe), and environment (Ee).

The probability of a given type (e.g. communications) and magnitude (e.g. major) of a human error (Oj) made by the individual or individuals com-

prising a given part of the design "team" in the loading analysis during the design phase ($Y_{1.2}$) could be evaluated as follows (Figure 9.12):

$$P[Oj \mid Y_{1.2}] = P[Oj \mid Oej]\,P[Oej] \cup P[Oj \mid Hej]\,P[Hej] \cup P[Oj \mid Pej]\,P[Pej] \cup P[Oj \mid Eej]\,P[Eej] \qquad (9.7)$$

where P[Oej], P[Hej], P[Pej], and P[Eej], refer to a human error of type j caused by organization factors, hardware factors, procedure factors, and environment (internal) factors, respectively.

Causes of Contributing Influences

The probability of the organization influence on the human error of a given type (Oj) occurring during the design phase in the loading analysis ($Y_{1.2}$) could be expressed as follows:

$$P[Oej \mid Y_{1.2}] = \bigcup P(Oejn) \quad (n = 1, \ldots, 8) \qquad (9.8)$$

The subscripts n = 1 through n = 8 refer to the organization error classification system developed earlier in this project. The eight classes of organization errors are identified in Figure 9.13. The eight mutually exclusive and exhaustive categories include communications, planning and training, culture, organization, violations, monitoring and controlling, ignorance, and mistakes.

The other terms (P[He], P[Pe], and P[Ee] would be developed in the same manner as P[Oe].

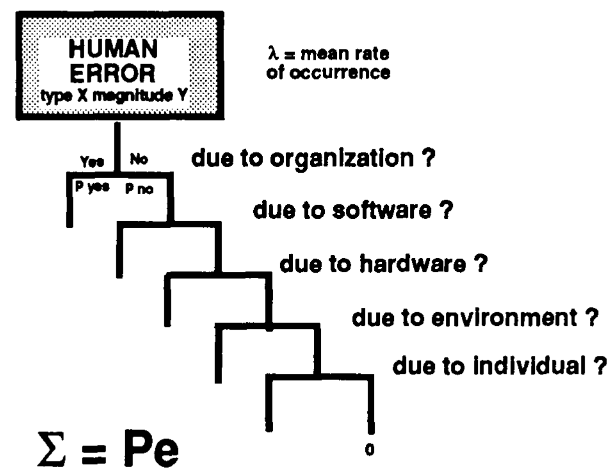

Figure 9.12 - Human error ETA

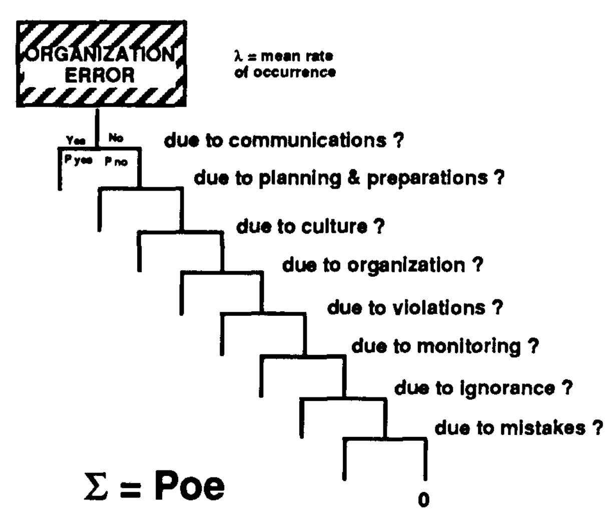

Figure 9.13 - Organization error ETA

System Diagram - Rare Event Approximation

The system diagram shown in Figure 9.10 has been based on the rare event approximation of the foregoing analytical expressions. Consistent with these developments, all of the direct and contributing EDA factors have been shown as elements in series. In this case, the following expressions can be developed.

Likelihood of insufficient quality:

$$Pf_Q \approx \Sigma\, Pfi \qquad \text{(i = 1 to 4, four attributes of quality)} \qquad (9.9)$$

Likelihood of insufficient quality in a given attribute due to "natural causes" (E) and due to "human errors" (O):

$$Pfi = \{Pfi_E \mid O\}\, P[O] + \{Pfi_E \mid Ø\}\, P[Ø] + Pfi_O\, P[O] \qquad (9.10)$$

Likelihood of human error causing insufficient quality in a phase of the life-cycle:

$$Pfi_O \approx \Sigma\, Pf\,[Yi \mid O_{Yi}]\, P\,[O_{Yi}]$$
$$\text{(i = 1 to 3, three life-cycle phases)} \qquad (9.11)$$

Likelihood of human error causing insufficient quality in one of four parts of the design phase (1.1 = configuration, 1.2 = loading analyses, 1.3 = structure analyses, and 1.4 = design documentation:

$$Pfi[Y_1 \mid O_{Y1}] = Pfi[Y_{1.1} \mid O_{Y1.1}]\, P\,[O_{Y1.1}] + Pfi[Y_{1.2} \mid O_{Y1.2}]\, P\,[O_{Y1.2}] + Pfi[Y_{1.3} \mid O_{Y1.3}]\, P\,[O_{Y1.3}] + Pfi[Y_{1.4} \mid O_{Y1.4}]\, P\,[O_{Y1.4}] \qquad (9.12)$$

Likelihood of human error causing insufficient quality in the loading analyses part of the design phase caused by the eight types of human errors:

$$Pfi[Y_{1.2}] \approx \Sigma\, (Pfi \mid Oj)\, P[Oj \mid Y_{1.2}]$$
$$\text{(j = 1 to 8, types of human errors)} \qquad (9.13)$$

Likelihood of one of the eight types of human errors (Oj) caused by one of the four principal causes or influences acting during the design loading analyses:

$$P[Oj \mid Y_{1.2}] = P[Oj \mid Oej]\, P\,[Oej] + P[Oj \mid Hej]\, P\,[Hej] + P[Oj \mid Pej]\, P\,[Pej] + P[Oj \mid Eej]\, P\,[Eej] \qquad (9.14)$$

Likelihood of a human error due to eight organizational influences occurring during the design phase:

$$P[Oej \mid Y_{1.2}] \approx \Sigma\ P(Oejn) \qquad (n = 1, ..., 8) \qquad (9.15)$$

These approximate analytical expressions equate to a series system that determines the quality of a ship structure. This is an interesting observation of the *quality system*. As additional elements are added to a series system comprised of *independent* elements, its probability of failure increases [Mansour, et al., 1990; Bea, 1990]. This indicates that the number of primary EDA in all parts of the quality process should be decreased to the minimum possible to decrease the likelihood of the system not developing the desirable level of quality. This emphasizes the importance of elimination of unnecessary complexity in all parts of the system.

The other interesting observation regards the effects of correlation between the series elements. If all of the series elements are highly correlated (magnitude of one EDA closely related to the magnitude of another EDA, etc.), then the probability of failure of the system is equal to the highest probability of failure in the system series *chain* [Bea, 1990; Orisamolu, Bea, 1993]. The reliability of a multi-element series system can be improved by high positive correlation. High positive correlation in EDA could be developed by human factors such as a consistent set of high quality individual (human), organization, hardware, and procedures factors that are allowed to permeate the entire design process. Organization culture is likely the most important of the correlating processes.

Detection & Correction

Thus far in this development, it has been assumed that there has been no explicit QA / QC in the process. Stated another way, the human error rates have presumed that there is no unusual *defense in depth* provided to detect and correct errors. In one way, this is not unreasonable. Most minor errors are caught by the individual or individuals involved in a particular process and corrected. In this development, we are concerned with the *major embedded errors* that can lead to significant degradation in quality that are not caught at the local level.

Consequently, the next step in this development addresses human error detection (= D) and correction (repair, = C). This is essentially an attempt to place parallel elements in the quality system so that *failure* of a component (assembly of elements) requires the failure of more than one *weak link*. Given the high degrees of correlation that could be expected in such a system, this would indicate that QA / QC efforts should be placed in those parts of the system that are most prone to error or likely to compromise the intended quality of the system.

A simple ETA of this process is given in Figure 9.14 for a major human error occurring in phase X of the life-cycle of the ship structure. The term *major* is used here because minor errors are generally detected and corrected either by the individual making them or by the group responsible for the particular activity. In this case, we are addressing those important errors that get through the normal QC process that has been defined by the QA system.

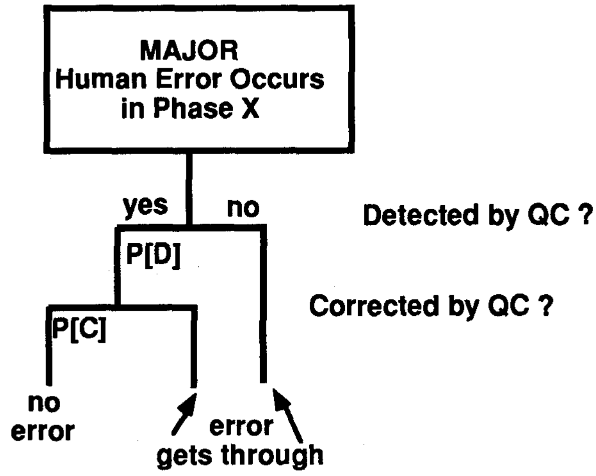

Figure 9.14 - ETA of human error detection and repair

Conditional on the occurrence of the human error of type (Oj, Figure 9.12), the probability that the error gets through the QA / QC system can be developed as follows. The probability of detection is P[D] and the probability of correction is P[C]. The compliments of these probabilities (not detected and not corrected) will be indicated as $P[\tilde{}D] = 1 - P[D]$, and $P[\tilde{}C] = 1 - P[C]$.

The undetected and uncorrected error event (Uej) associated with the human error event (Oj) is:

$$Ue = \bigcup (Oj \cap \tilde{}Dj \cap \tilde{}Cj) \qquad (j = 1 \text{ to } 8) \qquad (9.16)$$

The probability of the undetected and corrected error of type j event is:

$$P[Ue] = \Sigma\, P[Oj \mid \tilde{}Dj \cap \tilde{}Cj]\, P[\tilde{}Dj \mid \tilde{}Cj]\, P\,[\tilde{}Cj] \qquad (j = 1 \text{ to } 8) \qquad (9.17)$$

Assuming independent events, the probability of the undetected and corrected error of type j event is:

$$P[Uej] = P[Oj]\, \{P[Dj]\, P[\tilde{}C] + P[\tilde{}D]\} = 1 - P[D]\, P[C] \qquad (9.18)$$

The probability of error detection and the probability of error correction obviously play important roles in reducing the likelihood of human errors compromising the system quality.

Note that in the developments that preceded the introduction of QA / QC considerations, if P[Oj] were replaced with P[Uej], the effects of QA / QC could be introduced into any of the parts of the system.

The probability of detection will be a function of the quality and intensity of the QA / QC directed at this function. Similarly with regard to the probabil-

ity of acceptable or adequate correction. In both cases, an expenditure of resources is required to achieve the desired objectives.

The problem is to determine where QA / QC efforts should be directed, how they should be directed, and how intensely they should be developed. Given limited resources to develop quality in a marine structure, this is probably the single best reason for quantitative analyses; to help show the most effective way to implement QA / QC efforts throughout the life-cycle of the ship structure.

Due to the limitations in the scope of this first SSC project on HOE in design and construction of ship structures, it was not possible to conduct comprehensive and detailed analytical studies of ship structures and the elements, components, and systems that determine their quality. This should become the objective of future SSC sponsored projects.

However, in the remaining parts of this chapter, examples will be developed to illustrate how such qualitative and quantitative evaluations could be developed. In the next chapter, based on experience with other marine and non-marine structures, general guidelines and recommendations will be made on how QA / QC activities might best be directed in the ship structure design phase.

Example - Sleipner B Assessments

The background of the failure of the Sleipner A platform has been summarized in Chapter 6. This $ 1 billion catastrophe occurred after the highly successful design, construction, and operation of some 25 similar platforms over the past 25 years. These massive concrete and steel structures stand in water depths of 45 to 350 meters. A review of the history of these platforms has been summarized recently by Moksnes [1994]. In his review, Moksnes observed:

> *"The recent loss of the Sleipner A platform in 1991 was attributed to shortcomings in the interpretation of the results from the global analysis and inadequate design of a section of the cell walls, and points to the need for caution in what tends to be a highly automated design process. There is still a very important role to play for the experienced design engineer and the trained eye!"*

Noyes [1994] has performed quantitative evaluations of the design of the replacement platform: Sleipner B. Noyes organized the design process as shown in Figure 9.15.

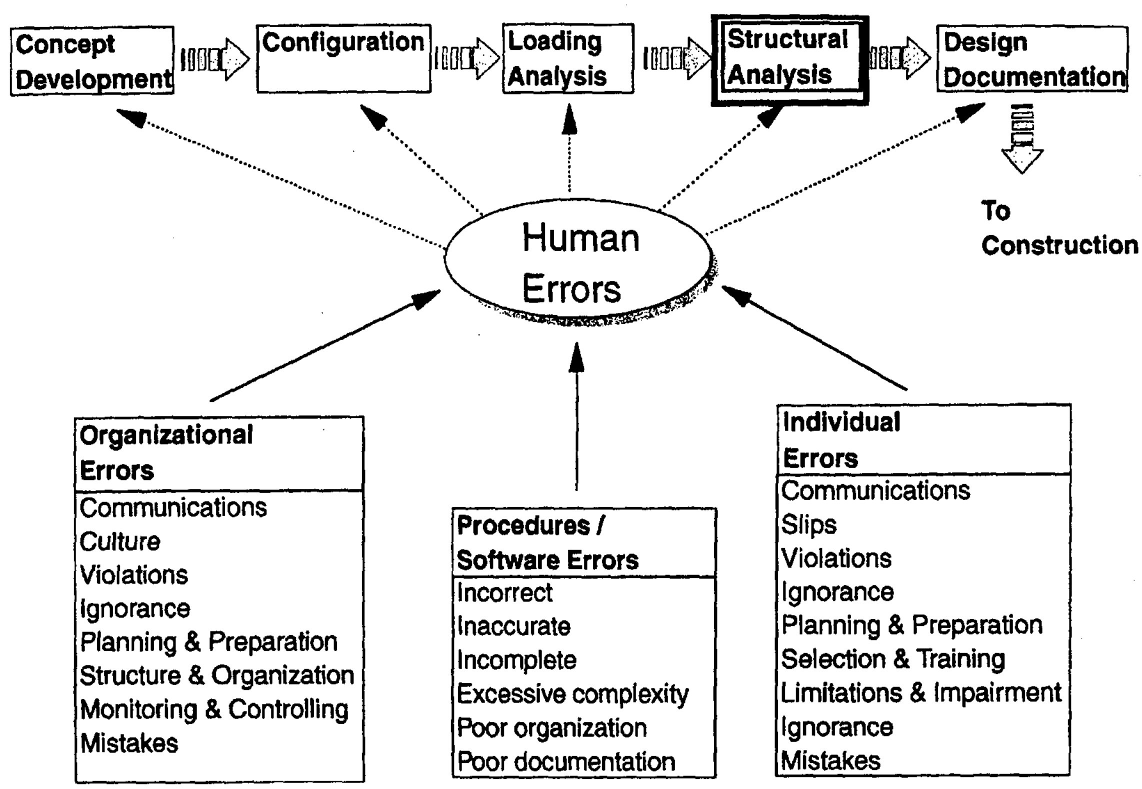

Figure 9.15 - Evaluation of the potential contributors to HOE in the Sleipner B structural analysis

Following an initial qualitative screening process and based on the diagnosis of the causes of the failure of Sleipner A, Noyes evaluated one primary contributor to lack of quality in the replacement platform: the Structural Analysis identified in Figure 9.15. The portion of the structural analysis evaluated was that of the finite element analysis of the star cell intersections that had been improperly performed in the Sleipner A design.

In addition, Noyes identified three potential primary contributors to lack of structural analysis quality in the Sleipner B structure. These were: 1) Organization Errors, 2) Procedure - Software Errors, and 3) Individual Errors. Identification of the principal types of these errors are summarized in Figure 9.15. Based on the error classifications that have been developed previously in this report, Figure 9.15 identifies the potential types of errors in each of these three categories.

Based on results of interviews with experts in performing Finite Element Analyses (FEA), Noyes identified five primary processes involved in performing FEA of CSD: 1) defining geometry limitations, 2) choosing elements, 3) choosing appropriate element meshes, 4) defining material properties, and 5) defining boundary conditions.

Based on the results from the interview of FEA experts and the results from a coarse qualitative screening analysis, Noyes identified the choice of appropriate element mesh sizes as a key potential source of error in the structural analysis. Fault Trees were used to perform and document the analyses (Figure 9.16). The base rate error probabilities were based on research performed and published by Williams [1988]. These results have been summarized in Chapter 8.

Three primary potential contributors to the probability of an error in the mesh size (Pe) were identified (Tree 1, Figure 9.16):

1) an error resulting from inadequate personnel selection and training (Pte),

2) an error resulting from ignorance on the part of those performing the analyses (Pie), and

3) an error resulting from mistakes made by those performing the analyses (Pme).

The probability of realizing an error in the mesh size was taken as the sum of the three contributing probabilities. The cross-product probabilities representing compounding events were neglected.

Tree 1

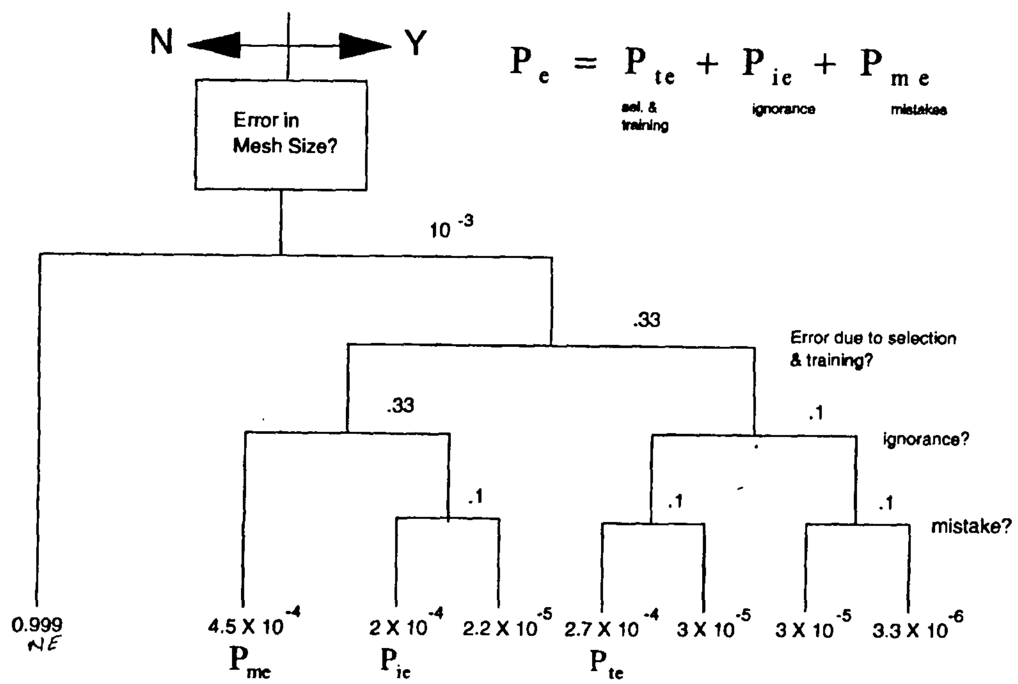

Figure 9.16 - FTA of the three primary contributors to an error in determination of the proper mesh size in the structural analysis

Tree 1 represents the final evaluation of the potential contributors to the basic fault: an error in the finite element mesh size. Subsequent trees (Trees 2 through 4) were used to define the primary causes of the three primary potential contributors of errors and to determine the associated probabilities.

Tree 2 (Figure 9.17) defines the organization and procedure related causes of the three major types of errors. Tree 3 (Figure 9.11) defines the primary contributing and compounding organization causes. Tree 4 (Figure 9.12) defines the primary contributing and compounding procedure causes. These causes were based on the organization and procedure taxonomies discussed previously. The evaluation of the major contributors was based on the results from an initial qualitative evaluation of these design elements.

For example, an error due to a mistake (Tree 1, Figure 9.16) could be due to either organization or procedures (Tree 2C, Figure 9.17). The organization caused mistake could be due to the organization culture or due to inadequate monitoring and controlling (Tree 3C, Figure 9.18). These two categories of organization causes were identified in the first phase quantitative evaluations as being the most dominant or important.

The mistake due to procedures could be due to excessive complexity in the procedures or due to inadequate documentation (Tree 4C, Figure 9.19). Again, these two categories of procedure causes were identified in the first phase quantitative evaluations as being the most dominant or important.

Identification of the primary causes of organization and procedure errors were based on Noyes study of the Sleipner A failure documentation and her quantitative evaluation of the process used to analyze the star cell intersection stresses. Evaluation of the probabilities associated with these causes were based on Noyes' subjective judgment and the *performance shaping factors* research published by Williams [1988] and summarized in Chapter 8.

Given these evaluations of the "prior" probabilities (based on the Sleipner A scenario), Noyes was able to identify the likelihood of a mesh sizing error, Pe. The results (Tree 1) indicated that this probability was Pe $\approx$ 1 E-3 (during the design phase, refer to Figures 8.3 and 8.4 for basis). Fifty percent of this probability was due to an error caused by personnel selection and training. This was the *primary initiating event or root* cause of the Sleipner A sinking.

Noyes then evaluated how changes in the organization and procedures could be implemented to reduce the likelihoods of an error in mesh sizing. Noyes used the results of the work published by Roberts [1993, 1994] to characterize organizational improvements and the work by Williams [1988] to characterize the quantitative effects of such improvements (refer to Table 8.2 for basis). Noyes used the work of Melchers [1987], Stewart and Melchers [1985, 1986, 1987, 1988, 1989], and Stewart [1990] to characterize improvements in procedures and the effects of increased monitoring and controlling.

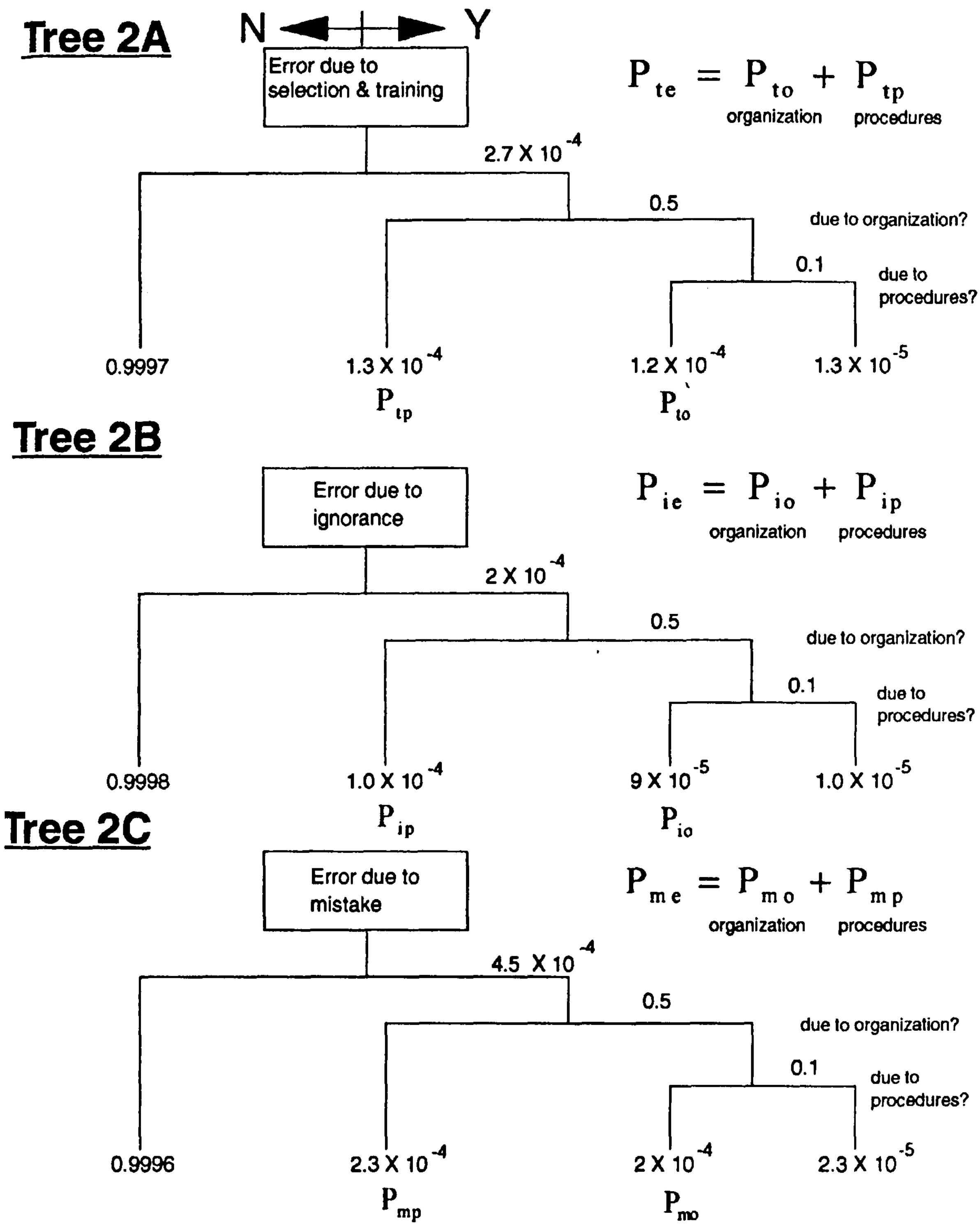

Figure 9.17 - Tree 2 - determination of design errors caused by organization and procedures

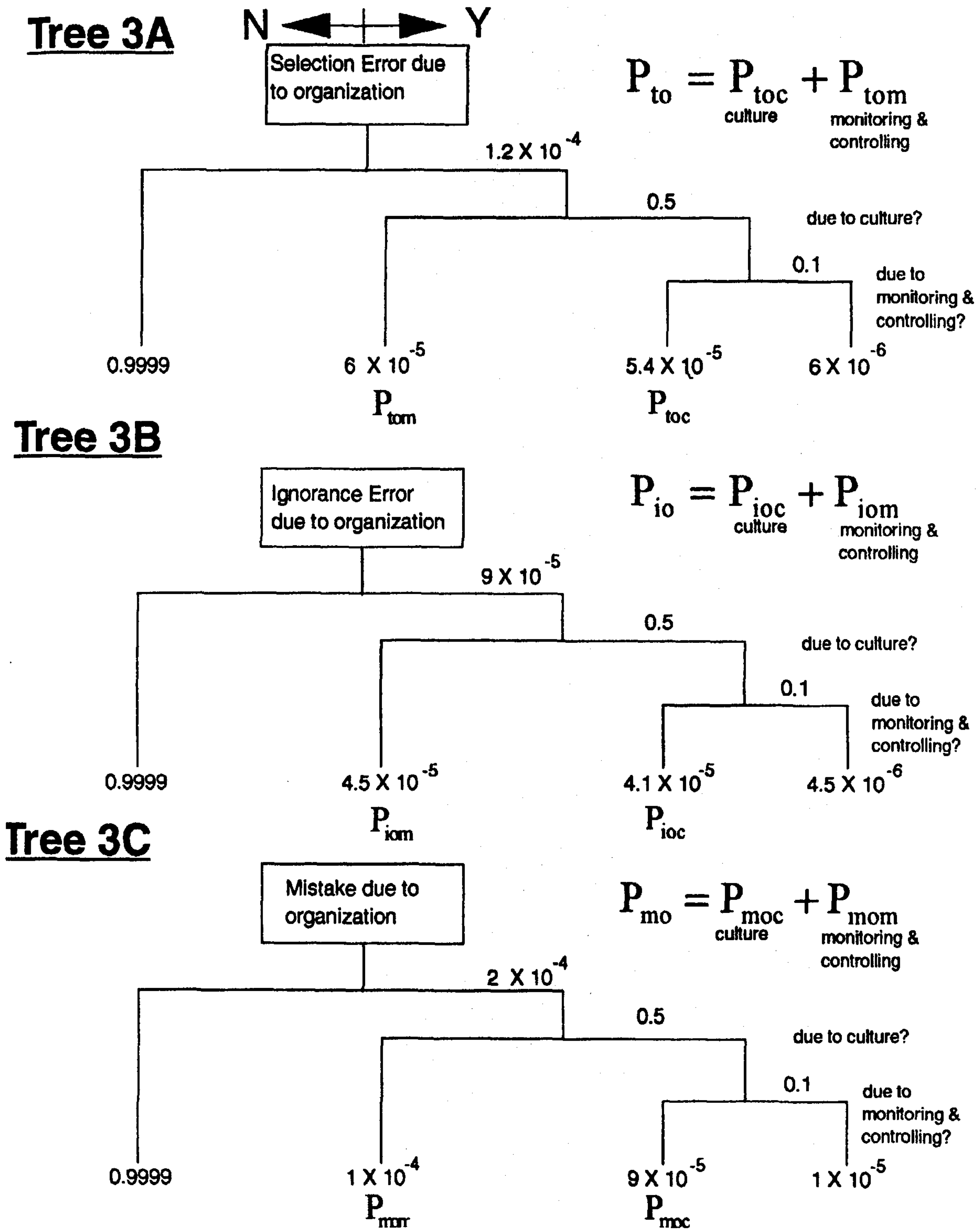

Figure 9.18 - Tree 3 - determination of organization errors (culture, monitoring & controlling) leading to an error in the mesh sizing

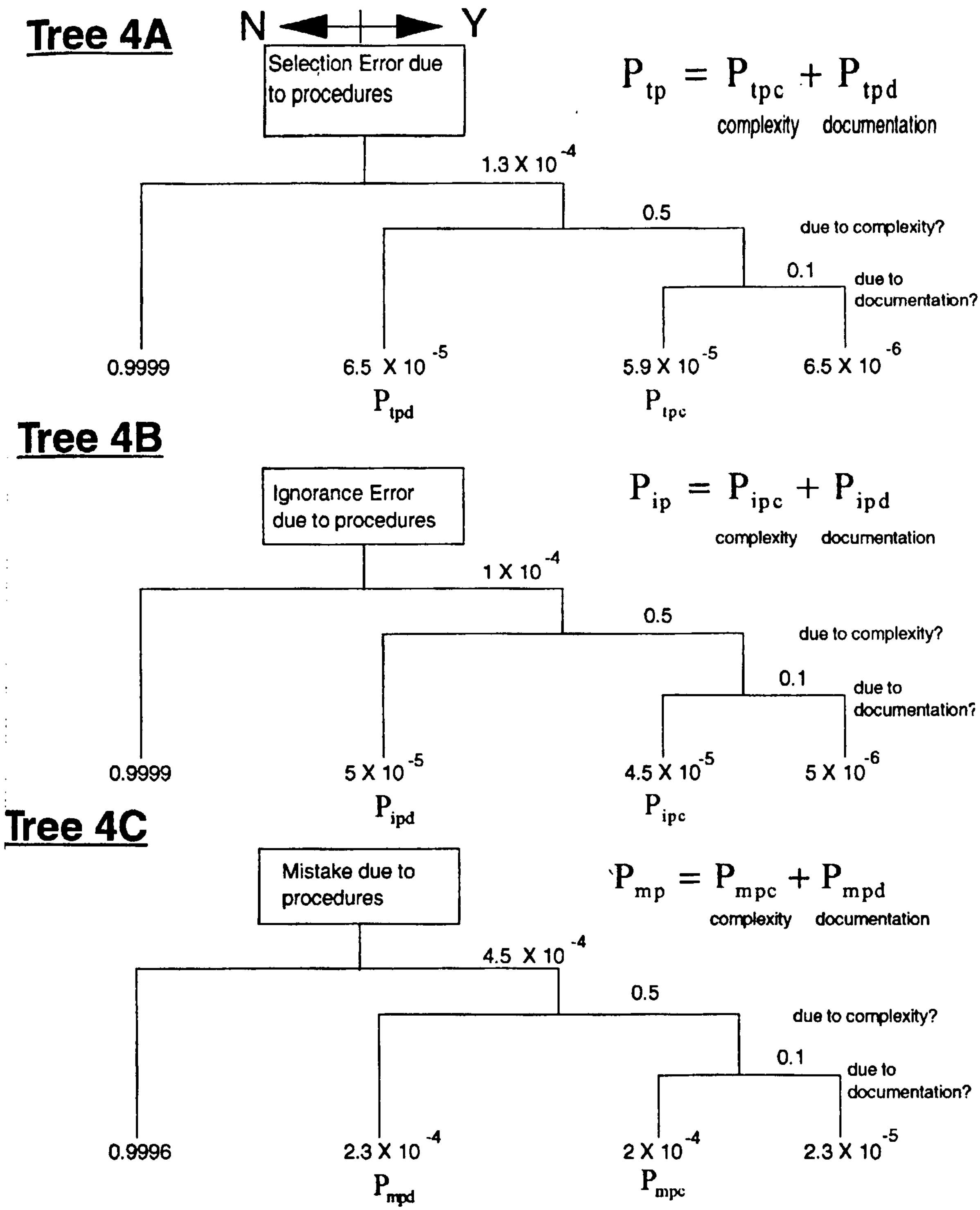

Figure 9.19 - Tree 4 - determination of procedure errors (complexity, documentation) leading to an error in the mesh sizing

Table 9.1 summarizes the results of Noyes study of the effects of various QA / QC measures (requiring organization and procedure changes) on the structural analysis error rate. The single most effective measure was an organization improvement in the selection of designers (design organization requirement for additional design engineer experience). This measure reduced the error rate by 77 percent.

The second most effective measure was an organization improvement in a requirement to increase the scope of outside checking. This measure reduced the error rate by 36 percent. Reductions in time pressures and improvements in training had comparable effects; reducing the error rate by about 20 percent. Improvements in documentation was the least effective measure; reducing the error rate by about 10 percent.

Table 9.1 - Effects of alternative QA / QC measures in reducing the likelihood of structural analysis errors in determining the finite element mesh sizes

QA / QC measure	Source of Error Impacted	Net Change in Total Error - %
Organization - improved training of designers	selection and training	-22
Organization - improved selection of designers	selection and training ignorance	-77
Procedures - improved documentation	procedure errors due to documentation	-13
Organization - reduce time pressures / constraints	mistakes	-20%
Organization - increase outside checking	monitoring & controlling mistakes	-36 %

The next step in such an evaluation would be to perform cost - benefit analyses of these alternative improvements to determine which measures should be implemented. This would involve a determination of the base rate of errors that could be tolerated (acceptable probabilities of failure). Such an evaluation was not performed by Noyes, but was performed by Rettedal, Gudmestad, and Aarum for the design and construction of the Sleipner B platform [1994].

The study performed by Retedal, Gudmestad, and Aarum [1994] utilized an approach very similar to that used by Noyes [1994]. They structured their analyses using ETA and FTA. These analyses and evaluations primarily evaluated equipment and structure systems. The human and organization elements were not explicitly evaluated. They were integrated into the back-

ground to define equipment, structure, and activity failure rates. They did not use any formal HOE structure or classification system.

Retedal, Gudmestad, and Aarum [1994] performed a very comprehensive evaluation of the key phases of construction including towing to location and commissioning the Gravity Base Structure (GBS). They evaluated the effects of improvements in the equipment, structure, and human activity elements of the GBS construction. They developed *tolerable or acceptable* error rates that the improvements were intended to develop. There were no explicit cost-benefit evaluations of the alternative improvements.

Table 9.2 defines the probability of failure that Retedal, et al. (Statoil) defined per project dependent on the extent of the project loss that would be represented by the failure. The *intolerable risk level* represented the *boundary* between acceptable and unacceptable probabilities of failure. These failure rates were then defined on a *per operation* basis (e. g. submergence testing, deck transport, deck mating, hook up, tow out, installation). These probabilities also are summarized in Table 9.2.

While these target probabilities did not explicitly evaluate cost aspects, they were based on historical experience with these types of systems. At the time of the initiation of the Sleipner B, the primary focus was on prevention of the type of errors that had lead to the sinking of Sleipner A. In the light of the schedule and productivity pressures, *prevention costs* were not a primary consideration.

Table 9.2 - Probabilities of Failure Per Project and Per Operation in Construction of Sleipner B GBS

Loss (%)	Probability of Failure Per Project		Probability of Failure Per Operation	
	negligible	intolerable	negligible	intolerable
100 (total loss)	1E-5	5E-4	1E-6	5E-5
50 (major damage)	1E-4	5E-3	1E-5	5E-4
10 (minor damage	1E-3	5E-2	1E-4	5E-3

Table 9.3 summarizes the results of damage probabilities determined by the analyses before and after *operator error risk reduction measures*. These measures included provision of construction weather instrumentation and criteria, training of crane operations personnel, improvements in communications systems and procedures, training in solution of special (critical) problems, simulator training, and detailed pre-lift planning.

These comprehensive measures addressed human, organization, system, procedure, and environmental aspects of the critical aspects associated with construction of the Sleipner B GBS. Note that several of the measures reduced the likelihoods of damage by 40 % to almost 70 %. The most effective measures were concentrated in the mechanical installation operations.

The authors note that both HazOp (qualitative evaluations) and QRA (quantitative evaluations) should be performed in making such analyses. Much was learned from each of the approaches about how to improve the system and where protective measures should be placed. The quality of the QRA was improved as a result of the HazOp study.

These measures were effective for the Sleipner B GBS was successfully constructed in a record short time (one year) and installed without incident in the last quarter of 1993.

Table 9.3 - Damage Probabilities (x E-6) Before / After Error Reduction Measures

Construction Phase ------------------ Type of damage	After Slip Forming	Mechanical Installation	Commissioning
loss of stability			3.26 / 1.84 (-44 %)
shaft collapse		8.96 / 5.46 (-40%)	
construction shaft damage		98.0 / 71.6 (-27 %)	
installation shaft damage			65.2 / 36.7 (-44 %)
shaft dome penetration		24.3 / 12.8 (-47 %)	
cell dome penetration		11.6 / 7.8 (-33 %)	
dome collapse	3.26	0.59 / 0.24 (-60%)	
global dome damage	8.63	3.93 / 1.29 (-67 %)	
utility module damage		20.3	
system damage		8.3 / 5.59 (-23 %)	

Tanker Sideshell Longitudinal Detail Design Examples

Both of the following examples focus on *critical structural details* (CSD) in commercial tankers. A CSD is a section of the structure which experiences very high stress concentrations in comparison with the rest of the structure, and therefore requires special attention in the design and construction phases, and should receive close scrutiny in inspections and maintenance.

The example CSD that will be the subject of the two examples, the sideshell longitudinal to webframe connection, is illustrated in Figure 9.20. The first example will address the design of this class of CSD to assure sufficient fatigue durability. The second example will address the analysis of this CSD using current Finite Element Analysis (FEA) methods.

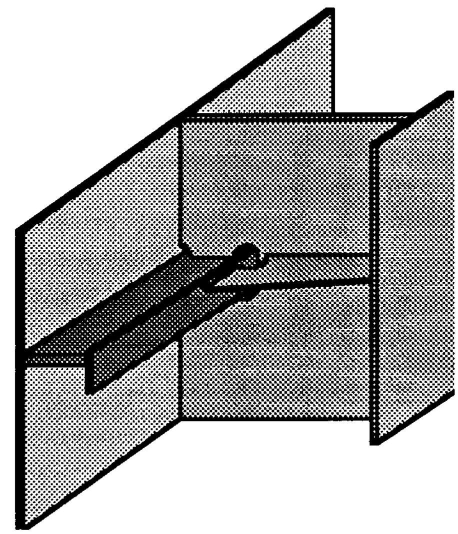

Figure 9.20 - Example CSD sideshell longitudinal to webframe connection

The CSD examples will be those from a class of six single-hull ships of 165,000 DWT (Figure 9.21). The mid-body transverse framing of this class of ships is shown in Figure 9.22.

These tankers are typical of the maritime industry tanker trade in general. They were built in the 1970's by a U. S. shipyard after being designed by an experienced U. S. naval architecture firm.

The ships were operated on a trade route that had very severe weather for most of the year. In a period of 15 years, these ships experienced approximately 3,000 significant fatigue fractures in CSD (Figure 9.23).

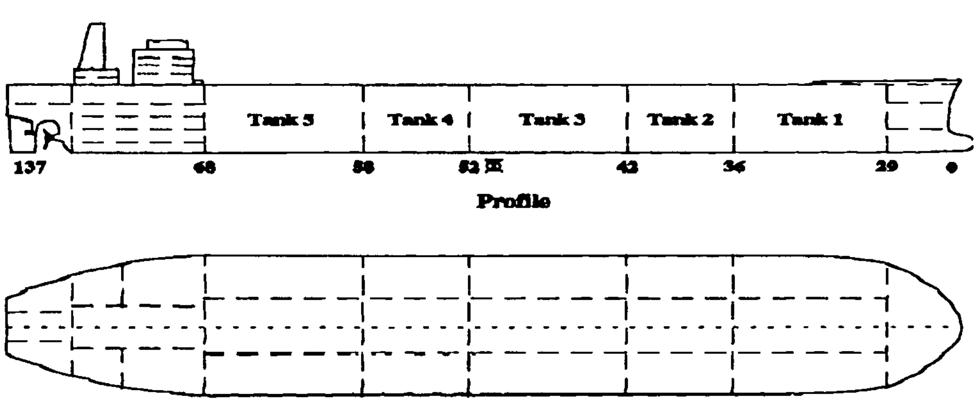

Figure 9.21 - Plan and profile of example 165,000 DWT tanker

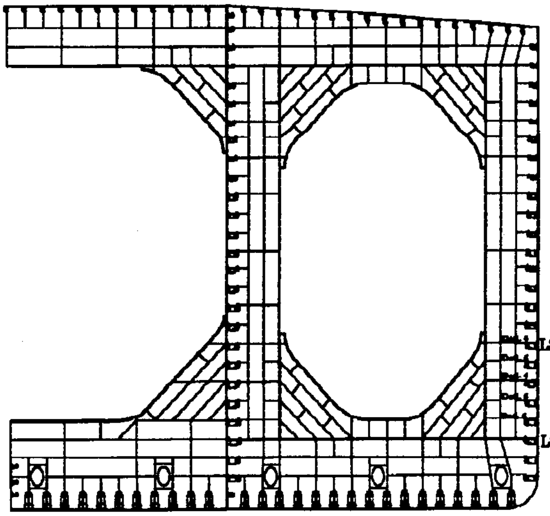

Figure 9.22 - Transverse midships frame of example tankers

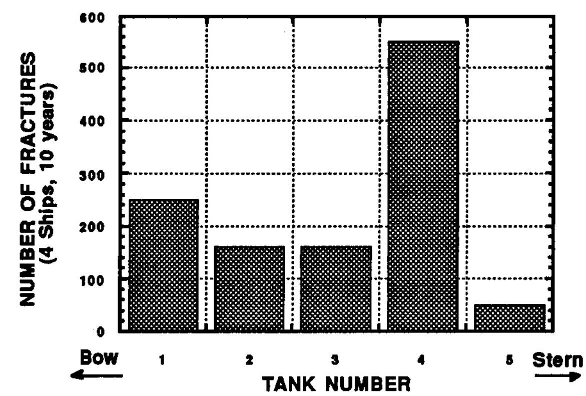

Figure 9.23 - Number of fractures in class of 165,000 tankers (4 ships in 10 years)

This propensity for fatigue problems resulted in regulatory repercussions. The ships were required by the U. S. Coast Guard to implement a Critical Area Inspection Plan (CAIP), which specifies the methods used by the vessel operators for documentation and tracking of structural failures. It must also contain the vessel fracture history, corrosion control systems, and previous repairs. The ships were required to undergo inspections once every six months, which meant taking the ships out of service, at great cost to the operator and owner.

Example 1 will address the fatigue design aspects of the CSD in the class of example ships. Example will address the Finite Element Analyses (FEA) of the same CSD.

Example 1 - Qualitative Analysis

The question posed in the analysis of this example is : *What is the cause of the marked susceptibility to fatigue problems in the CSD of the example class of ships?*

Study of the background and history of these ships indicates that there are many answers to this question [Salancy, 1994b]. The causes include actions (or inactions) by the ship builder, ship operator, regulatory agencies, classification society and ship owner, as well as the relationships between these groups.

This analysis attempts to address all of the major sources of fatigue susceptibility in order of occurrence, beginning with the existing climate in ship design and construction and carrying through operation of the ships.

Individual problems of the ships are addressed and a quality profile is carried out. The system is analyzed by event trees as it was configured and as it could have been re-configured, attaching quantitative values to the errors which occurred.

Fatigue Analysis

The most obvious source of fatigue susceptibility was the lack of fatigue analysis executed during the design of the ships. Was fatigue a known risk in engineered structures at this time? The answer is clearly yes [Nibbering, et al., 1973].

Fatigue has been the cause of some of the largest failures in the U.S. in recent history, including failures in the maritime industry. It has been estimated that from 50 to 90 percent of all structural failures are the result of "slow crack growth", or fatigue degradation [Petroski, 1985]. As discussed later in this section, fatigue analysis was well-known at the time of conception of these ships. Therefore, a major error in the design of these ships was the lack of fatigue analysis.

The issue of fatigue was not examined during the design process at all. No lab testing was carried out for fatigue. The reason for this exclusion was that fatigue analysis was not required by the regulatory and classification bodies. The climate in shipbuilding at the time was to build to requirements only.

The lack of fatigue analysis requirements was due to the relationship between the ship owners / builders / operators and the regulatory and classification societies. The owner / builder / operator believed that by building the ships to existing rules, sufficient safety and durability was ensured. However, the regulatory and classification societies considered only safety to be their responsibility, not durability, and therefore did not include fatigue in their guidelines. This situation had existed because durability had not been a problem historically, because ships built with adequate safety had also coincidentally had adequate durability as a result of the safety requirements.

In the case of these ships, that was not to be true, primarily because a new material (HTS, or *high tensile steel*) was being used in the structure, for which this circumstance did not apply. As this material was different from that which the regulatory societies had based their stance on durability on, durability was not ensured with the new material.

This error can be classified as one of organizational error. It can further be defined as an error in communications and culture. Communications was a problem because the rule-making bodies did not make clear that durability was not their responsibility when non-standard materials were used in a design. Culture was a problem because both the regulatory agencies and the classification society had been reducing requirements to appease ship builders

and attract clients, as well as to increase the economy of designs by lowering safety factors which may have seemed excessive in light of their success.

In the regulatory agencies rule developers had changed rules to go along with the interests of ship owners to build cheaper ships (Figure 9.24). The classification societies also reduced requirements. This was to ensure that they could compete with other classification societies for business -- if one society required something costly that another did not, it would most likely lose business. Another culture problem was the economic pressure being applied in ship construction. HTS was relatively untried in marine applications, but economic pressures to increase payload per deadweight ton forced its use.

Finally, the ships were to be operated on a trade route with severe wave loadings, which increased susceptibility to fatigue problems. This fact was not considered during the design phase. This error is considered to be one of culture. It is a sub-set of the larger fatigue analysis problem, and therefore is not treated separately. It was known that the planned route for the ships was one with severe environmental fatigue impacts, but the designers failed to take this fact into account, assuming that if the design passed the regulatory requirements, fatigue would not be a problem.

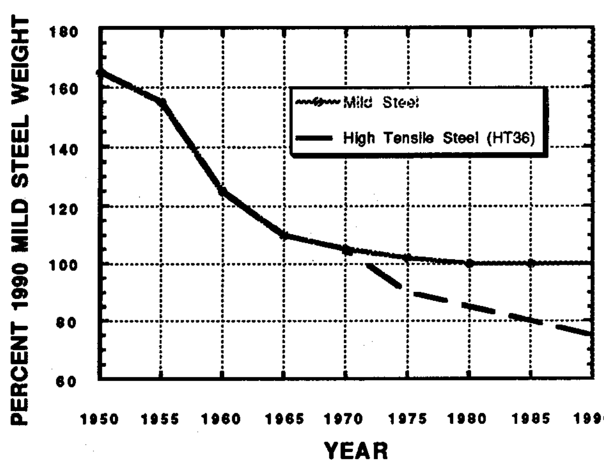

Figure 9.24 - Reduction in required minimum ship structure weight (100,000 DWT tanker) as function of time

This error should not be considered one of ignorance. Fatigue was a well-known risk in ship design at the time these ships were conceived. The 1967 edition of *Principles of Naval Architecture* [Comstock, 1967] contains a section on "Fatigue in Ship Structures", which discusses the use of HTS and describes the potential problems in "details subject to repeated reversal of high stress" (such as CSD). The section even includes the admonition:

> *"The fatigue limit of various structural steels is approximately proportional to the ultimate tensile strength of the material and not to the yield point. Therefore, fatigue may become an important consideration as higher yield strength steels are used."*

This advice would have been within easy reach of most naval architects at the time.

While an individual may have suspected possible fatigue problems, it was an organizational decision to design to regulatory guidelines and not to

carry out fatigue testing on HTS. Therefore, this error remains an organizational error. It should also be pointed out that fatigue analysis of large ships is a very complex problem. Fatigue analysis of offshore oil platforms and steel bridges has been carried out for many years, but ship analysis tends to be more difficult, for several reasons : the geometry of CSD are very complex, there are many of them, and the structure system and loadings are very complex. However, these same problems exist for airframes and they have been successfully conquered.

It is also interesting to note the historical relationship between required safety factors and major failures. Petroski [1985] points out that periods of prolonged success tend to inevitably invite failures, as prolonged success leads to a lowering of safety factors. This is because prolonged success seems to imply over-design to most designers, owners, and operators. These lowered safety factors eventually lead to failures.

In this case, the safety factors had been successful for fatigue, even if only because loading safety factors coincidentally insured fatigue success, which led to this type of failure when loading safety factors were (reasonably) lowered. This example also illustrates another point of Petroski's : apparently correct answers may be reached for the wrong reasons. Just because the ships in the recent past had not experienced fatigue problems by following loading safety factors did not ensure that future designs would also escape fatigue problems without undergoing fatigue analysis. An incorrect understanding of the system, which incidentally gives correct answers, can easily lead to failures.

Finally, Petroski warns against the potential dangers in designs with a high degree of newness, which seems relevant to the use of HTS in these designs.

> *"What appears to work so well on paper may do so only because the designer has not imagined that the structure will be subjected to unanticipated traumas or because he has overlooked a detail that is indeed the structure's weakest link."*

This would appear to be the case in this tanker design, where the fatigue properties of the structure were its weakest link.

In a recent article titled "Victory's Pipeline" Hannan [1994] cited three categories of problems that resulted in the structural failures that occurred in 521 T2 tankers built during World War II: design, workmanship, and material. Hannan observed:

> *"abrupt changes in section, or elements added to the ship as an afterthought, for example, often became troublemakers, initiating cracks and raising local stresses."*

"Imperfect welds were the point of origin for many failures. The imperfections originated as often the manner of preparing the joint for welding as in the quality of the metal deposited."

"The energy-absorbing capacity of the ordinary ship steel used was measured by impact tests and found to have a generally low value within the range of temperature in which the vessels operated. This led to brittleness. It was corrected by up-grading the steel specifications."

It would appear that many of the same problems encountered in the T2 tankers were repeated in the example class of ship structures.

CSD Configuration

The configuration of the ships made them fatigue-prone. Ship scantlings were reduced from historically average sizes and high tensile steel (HTS) was used. This was done to lighten the ship, as high strength steel allowed for a lighter ship than normal steel, increasing the amount of cargo per ton of displacement. However, the fatigue properties of HTS are not proportionally higher than that of mild steel, as discussed in the previous section. Therefore, the design of the CSD made the ships fatigue-prone. The CSD design did not adequately account for stress concentrations, which exacerbated this fatigue problem.

This can be classified as an individual human error. The design of the details was carried out by the design team, a relatively small group. This error can be further classified as one of selection and training. The error is considered of this type because stress concentrations should have been predictable, and the problem should have been detectable by a ship designer.

Construction Climate

The climate of ship construction at the time was one of low-bid to win contracts. This attitude resulted in attempts by the designer and builder to minimize costs at every opportunity. This led to cost-cutting in design as well as construction. This is an organizational problem, and is classified specifically as organizational error in culture. The existing culture did not promote or reward work of high quality, but work of low cost.

The state of the shipyards also lead to errors in the design and construction of the ships. Shipyards bid on the "minimum initial cost" ship to win contracts. This emphasis on initial cost drew attention away from life-cycle thinking, which lead to overlooking fatigue, corrosion and maintenance concerns.

The tankers had to be built in the U. S. because of the Jones Act, a piece of legislation which went into effect in 1921 and states that ships used on routes

between domestic ports must be built in the U. S. Therefore, the owners were forced to have the ship construction done by an industry that was not "up to par", as U. S. shipyards were clearly inferior to foreign yards in terms of productivity, quality, and technology. This can be proven by one single statistic : 3760 new commercial ship orders were placed between 1988 and 1992, with only 5 going to U. S. yards [Crawley, 1993]. The Jones Act ensured that the U. S. shipyards would not have to compete against foreign shipyards for this type of ship. This act removed at least some of their incentive for improvement.

U. S. shipyards were behind the times in terms of organization, and this may have had the greatest effect on their quality problems. Foreign yards were employing techniques such as modular construction, process lanes and zone outfitting. These methods allowed for simplified critical paths, greater quality control, and superior monitoring, and are described more fully in "Reconfiguration of System". In one study [Weiers, 1984] it was found that a Japanese yard, producing the same ship design as a US shipyard, required only 27% of the labor hours, and only 65% of the material cost.

The errors due to the climate of U. S. ship construction are classified as organizational errors. Specifically, they are errors of culture, planning and preparation, structure and organization, and monitoring and controlling.

Construction

This section focuses specifically on the execution of construction, as opposed to the overall planning and preparation of construction. Construction of high quality, robust ships may have resulted in ships resilient to errors committed in the design phase, as well as in operation. However, low quality construction appears to have resulted in error-intolerant ships.

The construction quality of the ships was generally poor [Salancy, 1994a]. Misalignments, poor fit-up, incomplete and poor quality welding, hand flame-cut edges, and poorly applied, low durability coatings were found. Poor edge preparation of CSD was also common. Commissioning inspections performed by the shipyard, the regulatory agency, the classification society, and lastly, the owner all disclosed incompletely welded CSD. Each of these inspections disclosed different numbers and locations of incompletely welded details. Existing QA / QC measures failed to detect and correct the wide variety of problems that arose during construction.

The errors which occurred in construction are considered to be individual human errors. They are due to ignorance, selection and training, slips, and planning and preparation. Most of these errors can be attributed to the state of U. S. shipyards at the time.

Operation, Maintenance, Repair

Although this example focuses on HOE during design and construction, the operation of these ships shows how operation can act to exacerbate errors begun in the design and construction phases. This seems to further support Perrow's claim that the maritime industry is "error-intolerant" as well as Petroski's assertion that "all errors are design-initiated". The ships in question were operated without regard to damaging conditions, typically operating at full speed in severe seas. This further exacerbated the fatigue susceptibility of the ships, by subjecting them to more frequent, higher stress cyclic loadings. This scenario probably could have been foreseen by the designers.

Maintenance of the ships was reduced below that historically typical in order to lower operating costs. Corrosion (general, pitted, and grooving) in ballast tanks reduced fatigue life of many structural details. This corrosion could have been stopped if maintenance had been adequate.

Finally, the quality of the repair work done on the CSD was poor. Repairs were not engineered. Repairs were frequently expedient or neglected to get the ships back in service.

All of these errors can be considered organizational and cultural, stemming from economic pressures to meet schedules, lower maintenance costs, and save on repair expenses. These errors are not examined in detail. However, it should be noted that they served to exacerbate the existing problems, rather than create new ones. This is further evidence that HOE prevention in the early stages of design and construction is more effective and efficient than management in later stages.

Quality Profile

This section describes a quality profile carried out on the example ships. This profile is used to determine the general quality to be expected of the ships, as well as to highlight the areas which are expected to have the greatest impact on quality. The quality scores are illustrated in Figure 9.25.

The ships are given low marks for *materials*, as HTS was relatively new to ship construction and this shipyard. Construction quality was poor, as mentioned earlier, so scores are low for *construction - procedures and systems*. The structure was not analyzed for fatigue, so both the *structure* and the *design - procedures and systems* are given low scores. Personnel and management were typical of a U. S. shipyard, so *construction - personnel and management* and *design - personnel and management* are given slightly below-average scores. Available technology (compared to foreign yards) was not employed, so the *technology* score is low. Finally, *financial resources, personnel resources, time resources* and *quality incentives* are all given low scores due to the climate at US shipyards at the time of construction.

Observations - Qualitative Analysis

The figure shows that in all of the categories, the ship structure quality factors were judged to be below "average." The ship structures were obviously prone to low quality: excessively low durability. The material (HTS) is the area of greatest concern. However, design, construction, and organization related issues lead to low quality scores. The provision of "below average" technology, time, personnel, and financial resources is a critical issue that is reflected in the low quality incentives. It is these key issues that will become the focus of the second part of this example; the quantitative analyses.

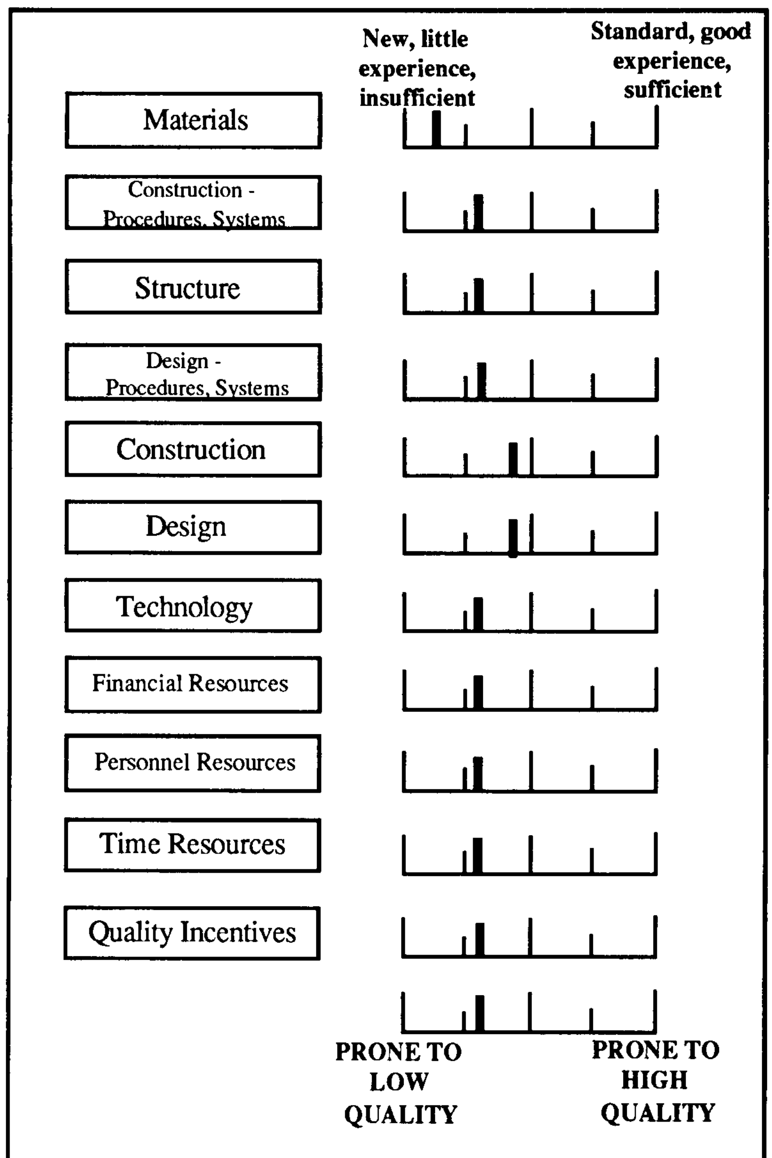

Figure 9.25 - Quality Profiling for Example Tankers

Example 1 - Quantitative Analysis

The qualitative analysis and quality profile highlighted four factors in design and construction which were major contributors to HOE. These four factors, and their specific type of HOE, are listed in Table 9.4. Corrosion protection was not considered a major factor, although it is a case of HOE. It is very similar to the CSD design, but its consequences were somewhat less immediate.

Table 9.4- Major factors and causes resulting in low durability CSD

Factor I - FATIGUE DESIGN ANALYSIS	
	Organizational Error, Communications
	Organizational Error, Culture
Factor II - CSD CONFIGURATION	
	Human Error, Selection and Training
Factor III - CLIMATE OF SHIP CONSTRUCTION	
	Organizational Error, Culture
	Organizational Error, Planning and Preparation
	Organizational Error, Structure and Organization
	Organizational Error, Monitoring and Control
Factor IV - SHIP CONSTRUCTION	
	Human Error, Ignorance
	Human Error, Selection and Training
	Human Error, Slips
	Human Error, Planning and Preparation

Analysis - Original System

The example is first analyzed for the original conditions. Each of the four factors is analyzed by an event tree. This required establishing baseline error rates for each factor. The baseline error rate for Factor I (error in the fatigue analysis) is 10^{-2} [Williams, 1988]. This rate has been selected because the error occurred in the omission of proper communication of responsibility.

Factor II (error in CSD design) has an error rate of 10^{-3}, as the design of CSD for fatigue was not well developed at the time. Factor III has an error rate of 10^{-3} also, as the state of US shipbuilding was the result of a confused set of relationships and dependencies, where errors could occur without much chance of being noticed. Factor IV has an error rate of 10^{-3}, as the construction process was slightly more complex than usual (HTS), and there were time and economic pressures.

The probabilities of the situations to induce errors being present are divided equally in this analysis. In the analysis of the re-configured system, these values may be reduced, as indicated by the "Multipliers for Performance Shaping Factors" [Rettedal, et al, 1994] and "Relative Strengths of Error-Producing Conditions" [Williams, 1988]. A large database of HOE would make it possible to predict the probabilities of these situations with greater accuracy. However, the main thrust of this report is to identify QA / QC efforts which will reduce these probabilities, so the actual probabilities are not as important in this report as the factor by which they are reduced.

The four factors are examined by event trees in the following figures. The trees begin with the baseline error rate and then divide evenly for each HOE situation.

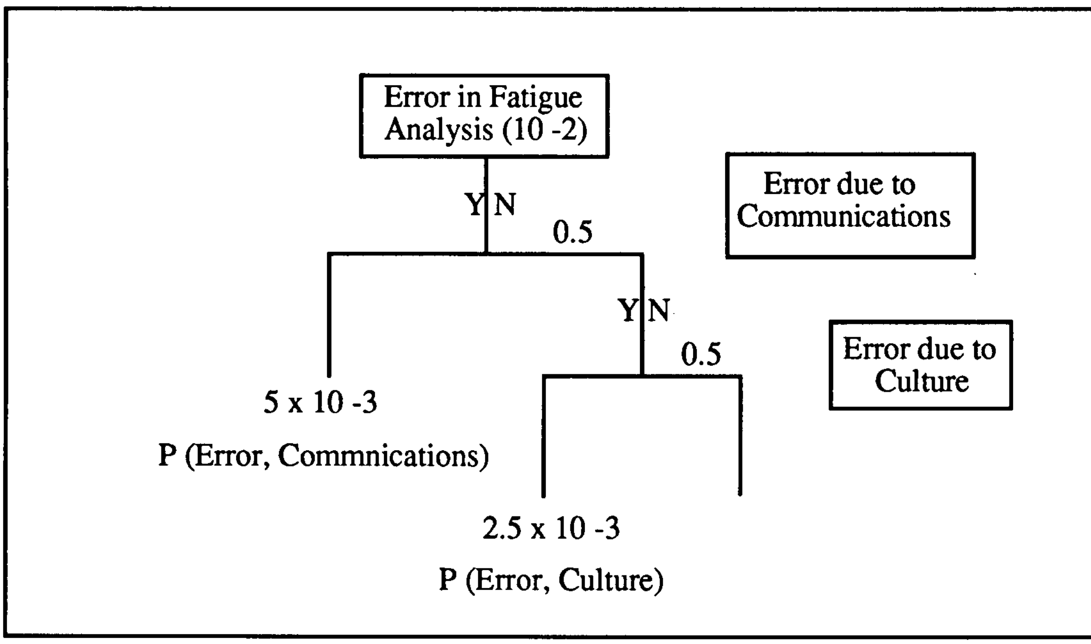

Figure 9.26 - Event Tree for Factor I

Figure 9.26 illustrates how the analysis will be carried out. A baseline error rate is assumed for the error in fatigue analysis. The situations which may exacerbate this error are added to the tree, and the probability of each situation occurring is given as 50 %. The total probability of an error occurring due to one of the given causes is found at the end product of each branch of the tree.

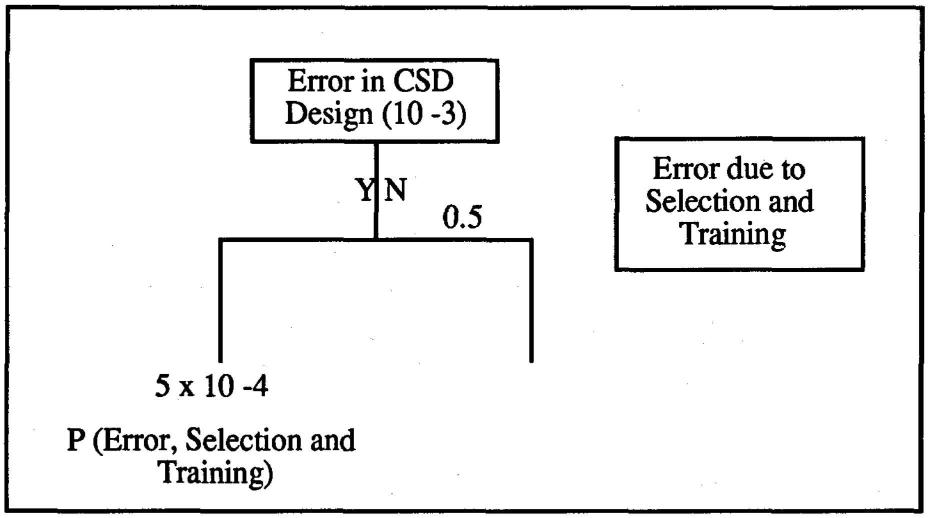

Figure 9.27 - Event Tree for Factor II

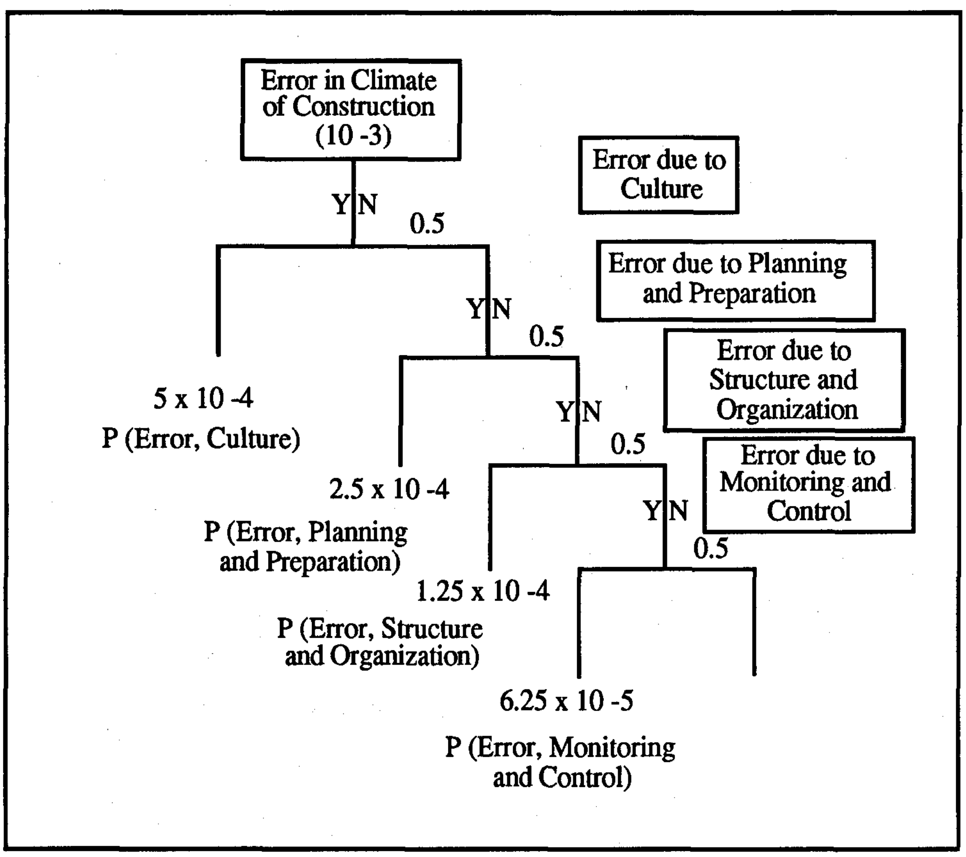

Figure 9.28 - Event Tree for Factor III

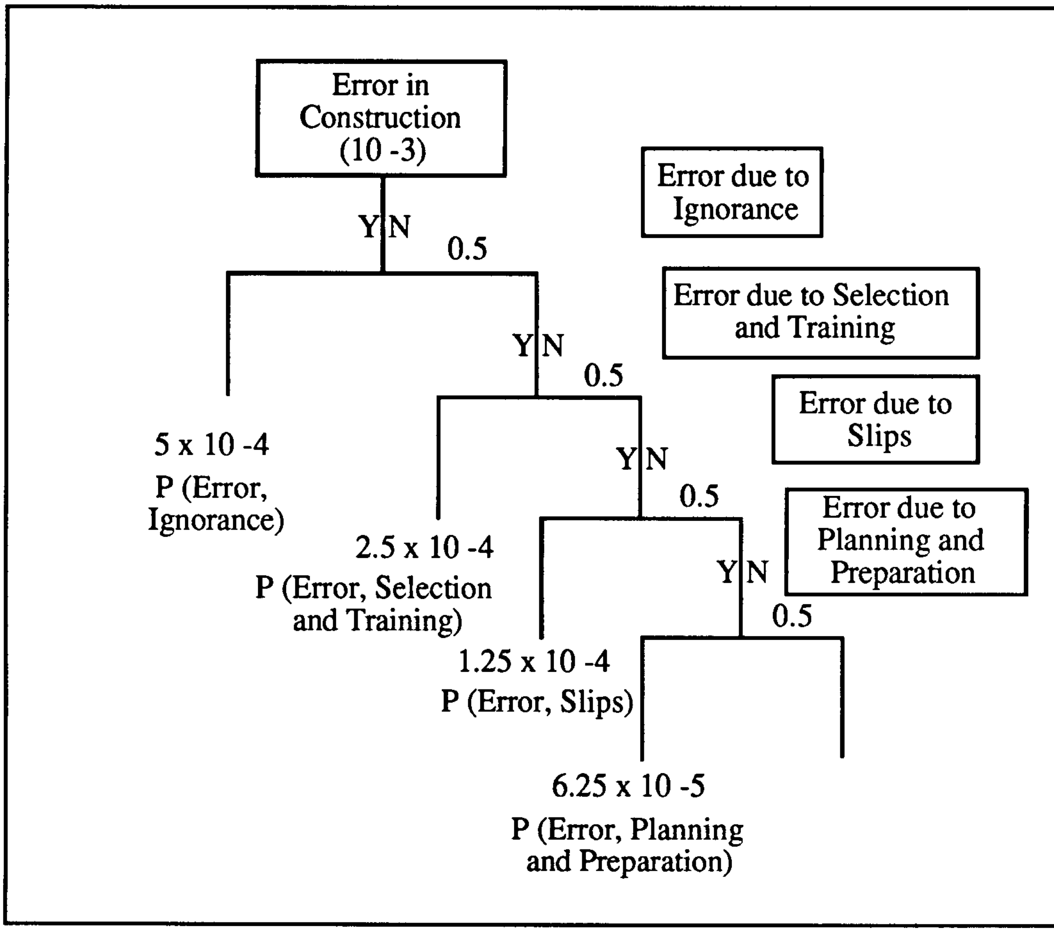

Figure 9.29 - Event Tree for Factor IV

Evaluation of Improved Design Alternatives

By the use of QA / QC measures the probability of occurrence of situations inducing HOE can be reduced. These measures are described for each factor in this section, and then quantitatively evaluated in the following section.

Factor I can be ameliorated by several organization-wide shifts in emphasis. Establishing clear lines of communication and responsibility between the various agencies at work in shipbuilding would greatly improve the problem and reduce the occurrence of conflicts of interest. An example of how responsibility can be defined is given below for the four agencies involved in ship design, construction, and operation : regulatory bodies, classification and inspection groups, designers and builders, and owners and operators [Bea, 1994a]:

- Regulatory : Definition and verification of compliance with goals and policies of quality.

- Classification and Inspection : Development of classification rules that will guide and verify design, construction, and operation of durable and reliable structures that meet regulatory and owner requirements.

- Design and Construction : Designing and producing structures with appropriate quality.

- Owners and Operators : Design and maintenance of high quality structures and the economic operation of structures.

However, this would be difficult to implement in the short-run. Focusing on the life-cycle costs of the ship could be a better means of improvement [Bea, 1994b]. When the economics are examined for the life-cycle, the advantages of initially robust design versus design for light weight and low initial cost should be obvious. The benefit of regular maintenance versus unexpected repairs will also be made clear. Focusing on resource allocation and accountability will also be beneficial.

Factor II can be improved by focusing on fundamentals and identification of failure modes. Ellingwood [1987] describes this type of error prevention measure :

> *"Technical measures include independent reviews of fundamental design concepts and assumptions, which have been identified as the root of many failures. Such reviews should be performed on all major projects. Even simple equilibrium and stability checks frequently reveal fundamental errors in design concepts and assumptions."*

Employees should be selected by their command of basic concepts and training should be carried out to help retain the fundamentals. Also, the recognition of "hazard scenarios" or failure modes should be emphasized. As Petroski pointed out, a designer can only design against failure modes which he or she recognizes. Other failure modes may be covered incidentally, but this can lead to dangerous situations. QA / QC measures towards improved designs would include licensing, verification and testing procedures, incentives, accountability, and job design.

Factor III presents a very complicated problem. The state of U. S. shipyards and the climate of construction in the U. S. is a product of many agencies. However, it is clear that U. S. shipyards have not kept up with modern advances in ship construction. Although some of the lagging can be attributed to lack of series ship orders and cost of equipment, much of the modernization in foreign shipyards has been in the form of organization [Weiers, 1984]. A ba-

sic reorganization of shipyard labor into more efficient units would greatly improve productivity.

There are four steps towards modern ship building practice which the shipyard that built the example class of ships could implement to improve quality and productivity:

1) Modular construction techniques should be employed. This serves to simplify planning and reduce interference between groups of outfitters.

2) Process lanes should be implemented [Salancy, 1994a]. These consist of fixed workstations which process items or units of similar construction. This enables workers to progress along the learning curve of construction and makes possible the use of statistical control in the production process. It also provides greater tool utilization, simpler material handling, and the tolerances necessary for successful modular construction. It can serve as a basis for implementing continual improvement and modern management techniques such as work teams and participate management.

3) Zone outfitting should be executed. This consists of outfitting by module, block, or unit. It has been estimated that outfitting by block saves 30% in labor, while outfitting by unit saves 70% over conventional outfitting [Weiers, 1984]. This improvement is the result of simplified coordination and scheduling and less time moving material through areas under construction.

4) Use standardized tested designs for subassemblies and units. This would work well with process lanes and zone outfitting. If plans were created and stored electronically, maximum utilization of CAD / CAM and FEA could be obtained. There would also be benefits due to re-use.

Establishing goals of quality and good customer relations over low-bid would go a long way towards improving the state of ship construction. Construction should also be viewed in terms of life-cycle costs.

Factor IV is also a difficult problem. The example of foreign shipyards could be followed for training, selection and organization. Reorganization would bring about the greatest quality change. However, reorganization would require workers with flexible skills. This would be a problem, as U. S. shipyards are currently approximately 90 % unionized, with the unions being craft-based [Stabler, 1993]. Without flexibly-skilled workers, the advantages of techniques such as zone outfitting cannot be fully realized.

Following the principles of design for constructability, inspectability, and repairability would be beneficial [Bea, 1992].

Analysis - Re-configured System

Based on the reconfiguration suggestions made in the previous section, the system is again analyzed by event trees, with new probabilities of occurrence (but the same base error rates).

In Factor I (Figure 9.30), the Communications error probability has been reduced by half. The awareness of communication problems should have some immediate effect, but actually changing the way the various agencies interact will be difficult and take a great deal of time. Similarly, the Culture error probability has been reduced by a factor of two. Putting emphasis on life-cycle considerations will have a good effect, but it will take a long time to overcome the existing economic pressures. Initial gains should not be difficult, but substantial change will be slow, hard work.

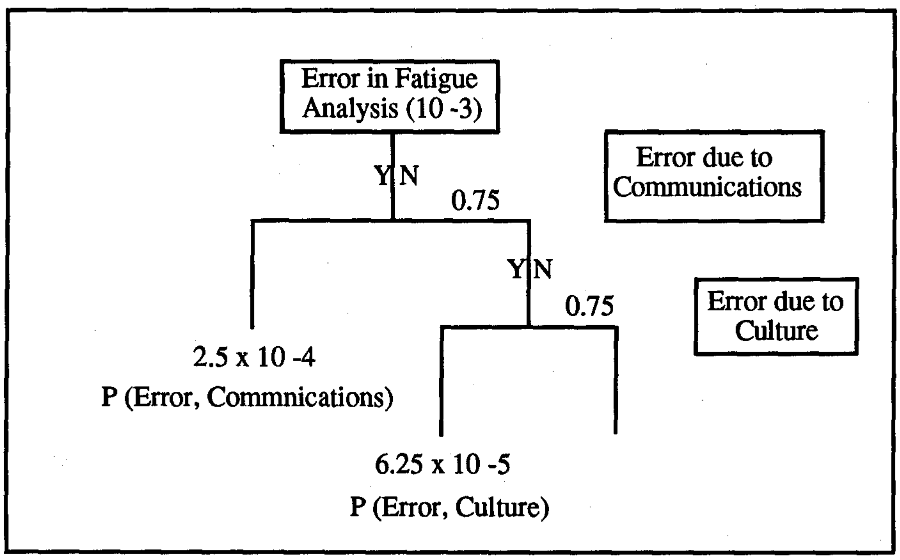

Figure 9.30 - Event Tree for Factor I, Re-configured

Factor II (Figure 9.31) would experience greater improvement through QA / QC measures. Focusing on fundamentals and failure modes would give designers a much better chance to detect large errors. Therefore, the probability of error due to Selection and Training has been reduced by a factor of five.

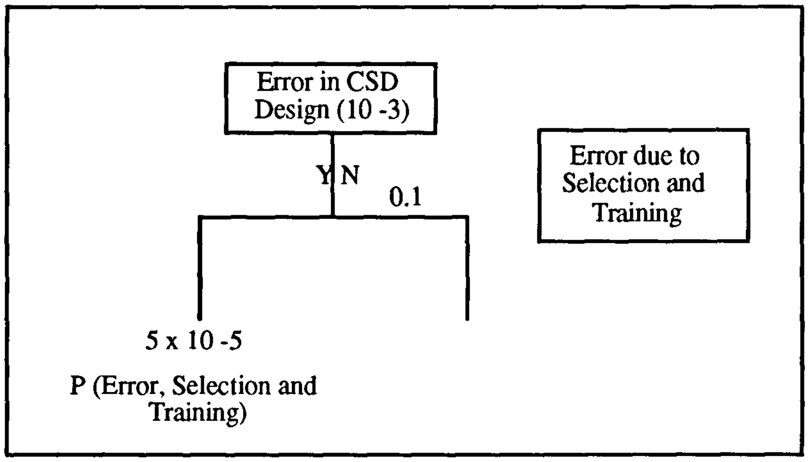

Figure 9.31 - Event Tree for Factor II, Re-configured

It is difficult to assess the impacts of improved QA / QC for Factor III (Figure 9.32). It is judged that focusing on life-cycle costs and quality would improve the Culture problem, reducing it by a factor of two [Bea, 1994b]. Adopting modern shipbuilding methods of organization, selection, and training could have a similar effect on Planning and Preparation and Structure and Organization. Implementing statistical control methods would have a large impact on Monitoring and Control, reducing its probability of contributing to error by a factor of five.

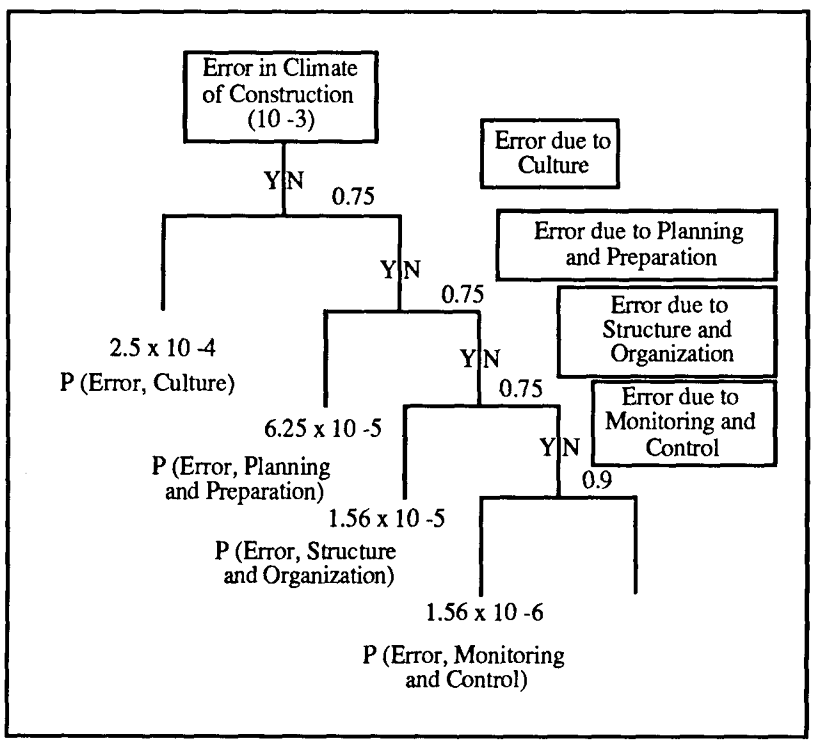

Figure 9.32 - Event Tree for Factor III, Re-configured

Factor IV (Figure 9.33) can be handled in the same manner as Factor III. Improved Selection and Training can be expected to cut error probabilities in half, if modern shipbuilding methods are employed. Probabilities of error due to Ignorance and Slips should also be decreased by the same amount. The greatest benefit would be in adopting modern methods of labor organization and construction planning. By using these methods, a reduction in error due to Planning and Preparation of a factor of five could be realized.

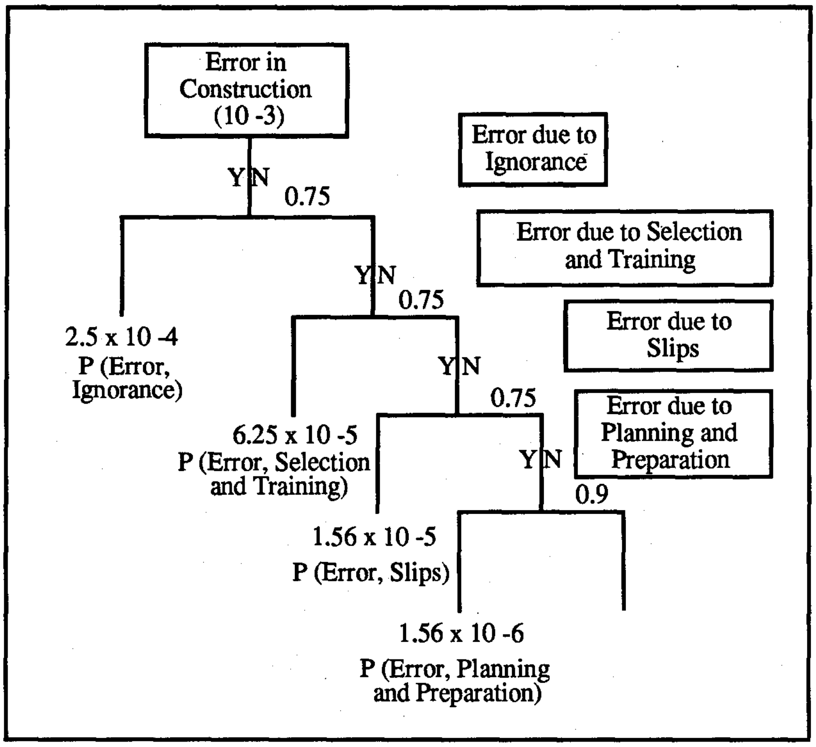

Figure 9.33 - Event Tree for Factor IV, Re-configured

Observations from Quantitative Analyses

Table 9.5 summarizes the quantitative results from Example 1. The evaluations indicate that in the initial state the likelihood of experiencing less than desirable fatigue durability in this class of ships CSD due to HOE problems was about 3 E-2. Given this less than desirable durability in the ships, the likelihood of fatigue failures in the CSD was about 1 E-1 (for a 15 year operating period) [Bea, 1993a; Schulte-Strathaus, Bea, 1993]. This class of ships were obviously *a problem waiting to happen.*

The largest contributors to the CSD durability problem were due to construction related issues, both of which had their roots in organizational issues. The construction related issues indicated a probability of durability failure of 2

E-2 while the design related issues indicated a probability of durability failure of 1 E-2.

As discussed, each of the four factors has means for improvement. Addressing the design issues, Factor I would be the most important element to concentrate improvement efforts on, as it has the highest baseline error rate of the design related issues. Development of fatigue design guidelines and requirements would clearly address this factor.

In the other factors, a new QA / QC effort for hiring and training, for both designers and yard workers, would have positive and significant impacts on quality. Some type of reorganization of shipyard labor will be necessary for improved quality control in construction, which will be a difficult problem, but is necessary to improve construction quality.

However, it appears the greatest problems are those which are classified as *organizational and cultural.* Changing these categories would have the best chance of changing the overall system from one which is considered *error prone or low quality inducing* to one that is *acceptable quality inducing, robust, and error-tolerant.* The positive interactions of the cooperating agencies (owner / operator, regulatory, classification, shipyard) oriented toward achieving acceptable quality in the ship structures are perhaps the most important change that could be made [Bea, 1994a].

Technical changes such as improved durability design guidelines are less important than organizational issues such as requirements that they be used and the provision of adequately trained personnel and other design resources. Similarly, it is organizational issues related to construction that are the most important; most of these are rooted in provision of sufficient resources (personnel, time, money) to achieve adequate quality in the ship CSD.

Table 9.5 - Summary of results from Example 1

FACTOR I : FATIGUE ANALYSIS		
Baseline Error Rate	*1.00E-02*	
	As Configured	As Re-configured
P Communications	*0.50*	*0.25*
P Culture	*0.50*	*0.25*
P Error - Communications	5.00E-03	2.50E-03
P Error - Culture	2.50E-03	6.25E-04
Total P Error	7.50E-03	3.13E-03
Net Change		**58%**
FACTOR II : CSD DESIGN		
Baseline Error Rate	*1.00E-03*	
	As Configured	As Re-configured
P Selection and Training	*0.50*	*0.10*
P Error - Selection	5.00E-03	1.00E-03
Total P Error	5.00E-03	1.00E-03
Net Change		**80%**
FACTOR III : CLIMATE OF US SHIP CONSTRUCTION		
Baseline Error Rate	*1.00E-03*	
	As Configured	As Re-configured
P Culture	*0.50*	*0.25*
P Planning and Preparation	*0.50*	*0.25*
P Structure and Organization	*0.50*	*0.25*
P Monitoring and Control	*0.50*	*0.10*
P Error - Culture	5.00E-03	2.50E-03
P Error - Planning	2.50E-03	6.25E-04
P Error - Structure	1.25E-03	1.56E-04
P Error - Monitoring	6.25E-04	1.56E-05
Total P Error	9.38E-03	3.30E-03
Net Change		**65%**
FACTOR IV : CONSTRUCTION		
Baseline Error Rate	*1.00E-03*	
	As Configured	As Re-configured
P Ignorance	*0.50*	*0.25*
P Selection and Training	*0.50*	*0.25*
P Slips	*0.50*	*0.25*
P Planning and Preparation	*0.50*	*0.10*
P Error - Ignorance	5.00E-03	2.50E-03
P Error - Selection	2.50E-03	6.25E-04
P Error - Slips	1.25E-03	1.56E-04
P Error - Planning	6.25E-04	1.56E-05
Total P Error	9.38E-03	3.30E-03
Net Change		**65%**

Example 2 - Qualitative Analysis

The second example analyzed in this report focuses on the finite element analysis (FEA) of the CSD developed in the first example. The naval architecture firm responsible for this design utilized the then current ABS Rules for Building and Classing Steel Vessels [ABS, 1991].

The goal of this example is to illustrate how HOE in FEA might be better managed; specifically in the global and local FEA performed in fatigue analysis of CSD by ship designers.

The observations pertaining to FEA in this example are based on interviews conducted during this project with users of FEA applied to ship structures. The observations are meant to be generic, and will vary in details according to the specific FEA analysis package employed. The example is not specific to a particular usage of FEA in design, rather it is an attempt to illustrate the potential problems stemming from the use of FEA in general, and particularly to the analysis of ship structures.

Currently, there are no definitive guidelines for the usage of FEA in ship structures, although some methods are under development [ABS, 1993; Ma, Bea, 1994; Schulte-Strathaus, Bea, 1993]. However, by the use of efficient QA / QC measures, it should be possible to gain acceptable and sufficient consistency and accuracy in FEA analysis.

Background

FEA is a numerical technique for physical responses of a structure to imposed loads, moments, and stresses [Hughes, 1988]. The use of the finite element technique became feasible and economical with the advent of high-speed computers which could carry out the thousands of equilibrium calculations required of an FEA model in a reasonable amount of time. However, the potential of FEA is still limited by the speed of computers, so the use and accuracy of FEA can be expected to increase in the future with increases in computing speed.

FEA seeks to define a structure "as an assemblage of individual structural elements interconnected at a discrete number of nodes" [Hughes, 1988]. In a continuous structure, such as a ship, the choice of what to model as an individual element can be difficult to determine, as continuous panels must be subdivided into separate finite elements for the modeling to work [Stear, Paulling, 1992; Zilikotto, et al., 1991].

FEA proceeds through a series of analyses that are intended to *zoom-in* on a particular CSD to determine the local hot-spot stresses [Hughes, 1983; Sumi, 1994]. This process is illustrated in Figure 9.34 - Figure 9.40.

First a global analysis of the ship is performed to determine the distribution of loadings through the length of the ship (Figure 9.34). Next, a section of the ship is identified (e. g. one tank space either side of the area of interest) and the boundary conditions / loadings to be imposed on the ship section determined from the previous step (Figure 9.35).

These boundary conditions are imposed on a coarse finite element model of the ship section of interest (Figure 9.36) [Stear, 1993]. The loadings and displacements are analyzed to determine the loadings and displacements close to the CSD of interest (Figure 9.37).

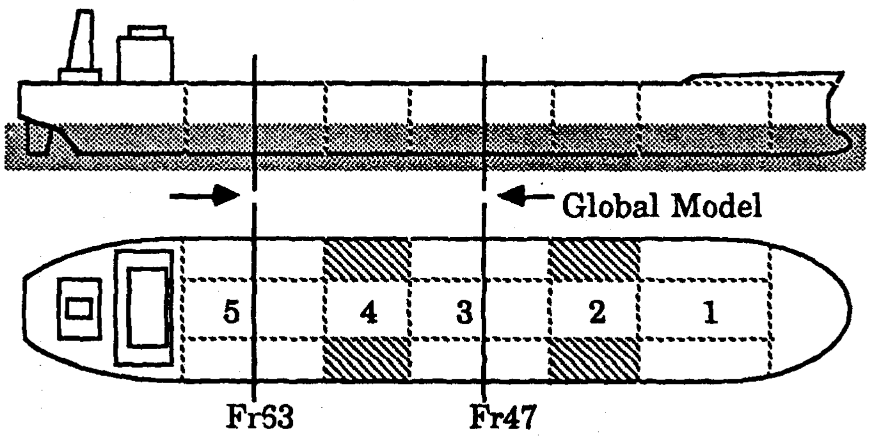

Figure 9.34 - Global model of tanker developed based on boundary loadings imposed one tank space either side of the tank being analyzed

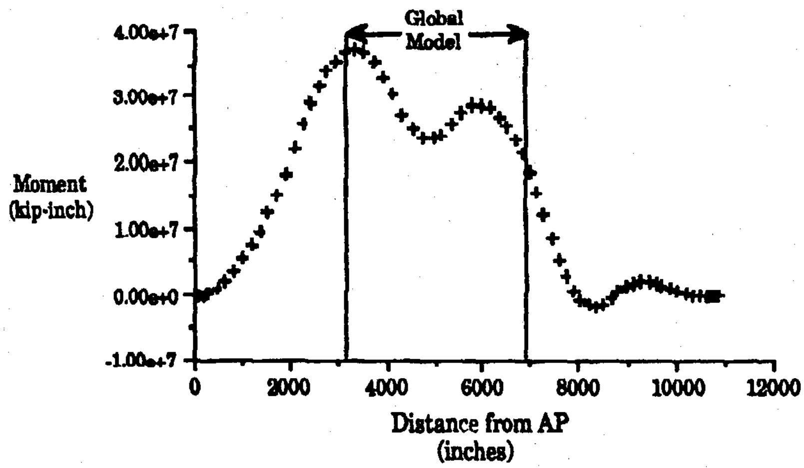

Figure 9.35 - Global loadings imposed on boundaries of global finite element model

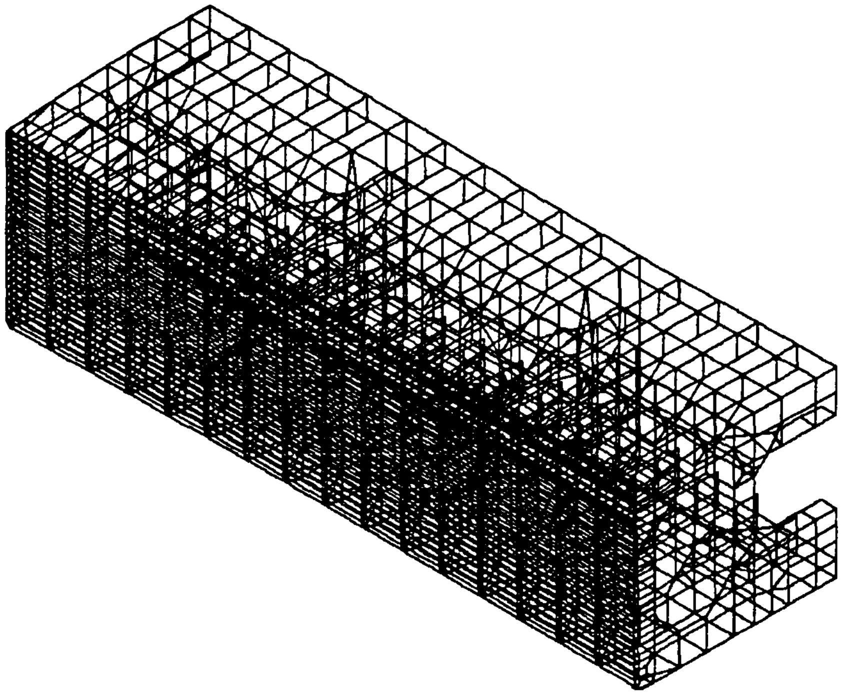

Figure 9.36 - Global finite element model

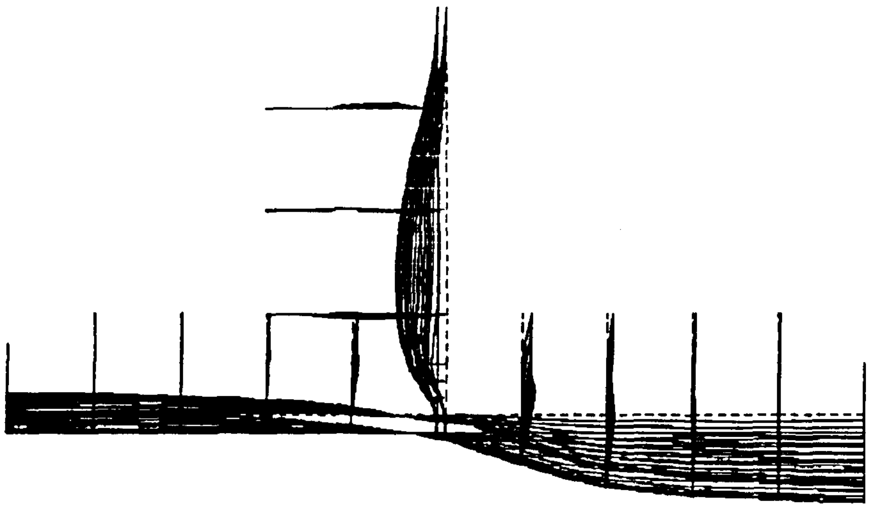

Figure 9.37 - Local displacements induced at boundaries of CSD

These local loadings and displacements are then imposed on a section that surrounds the CSD of interest and a gross finite element model developed of the CSD (Figure 9.38) [Stear, Paulling, 1993; Xu, et al., 1993].

Next, detailed fine-mesh FEA are performed on the CSD to determine the stresses (principal, crack opening) that are important to the strength and

durability of the detail (Figure 9.39). The final step is associated with determination of the hot spot stresses associated with each of the important loading conditions (Figure 9.40).

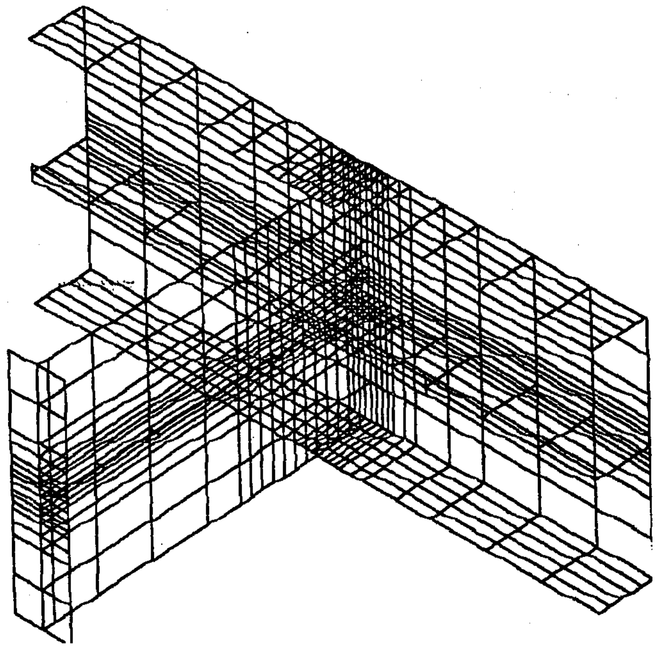

Figure 9.38 - Wire frame model of CSD

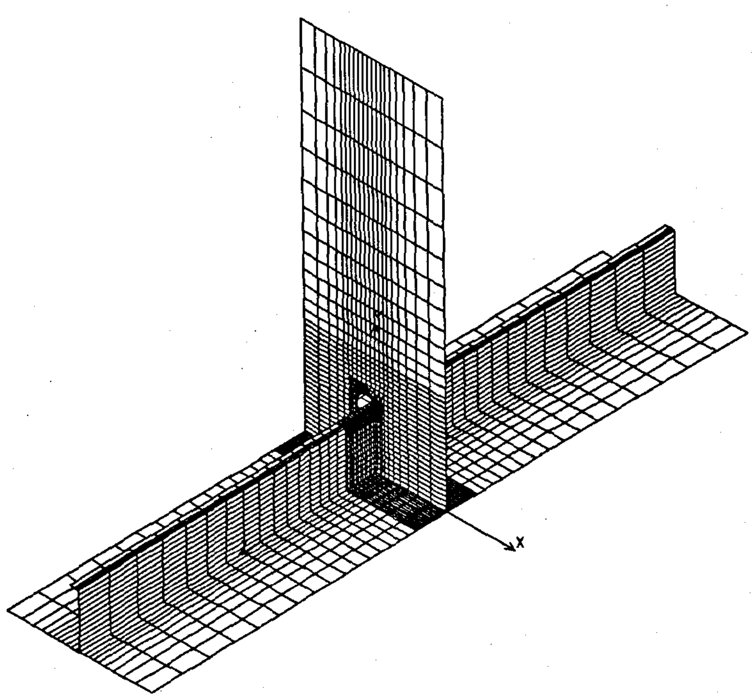

Figure 9.39 - Detailed FEA of CSD with boundary condition loadings and restraints

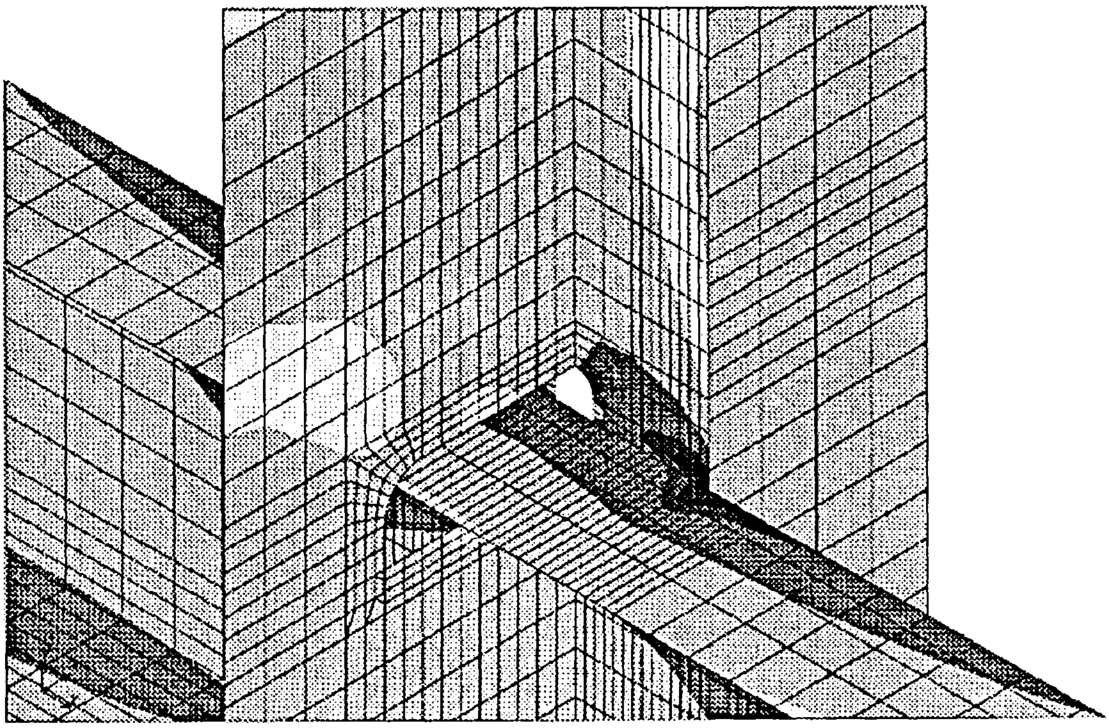

Figure 9.40 - Local hot spot stresses in CSD

At the local hot-spot level of the analyses, the choice of mesh size can lead to problems in compatibility which are difficult to detect [Ma, 1994]. Another potential source of problems is the sheer complexity of FEA models [Stear, 1992; Xu, et al., 1992]. Even simple models of structural details tend to have thousands of individual elements, making a finite element model very complex and, in almost all cases, too large to check by hand calculations.

FEA is commonly used in the analysis of ship structures to determine the "hot spot" stress ranges in fatigue analysis of CSD [Schulte-Strathaus, 1993]. These hot spots are the areas where the highest stress concentrations are expected to occur, and therefore where fatigue cracking is most likely to initiate. It is this level of FEA that will be addressed in this example.

FEA consists of the definition of : the type of elements, boundary / restraint conditions, mesh compatibility, and mesh size / aspect ratio. Individual human errors can be made in any of these determinations. The interviews documented by Noyes [1994] identified five important considerations in performing FEA:

1) defining geometry limitations - consideration of special methods required to model curved surfaces, to properly model stress gradients, and to accurately describe the behavior of the portion of the structure under consideration.

2) choosing elements - there are several types of elements (e.g. plain strain, plain stress, 2-dimensional, 3-dimensional) and these types of elements must be chosen to adequately describe the stress -strain behavior of the portion of the structure under consideration.

3) choosing appropriate element meshes and connectivities - the dimensions of the elements must be chosen to accurately determine the stress gradients and stress concentrations; the element meshes of different sizes and perhaps geometry composing a particular structural detail must be properly interfaced to prevent inaccuracies in the critical stresses.

4) defining material properties - stress-strain properties such as the modulus of elasticity, yield stress - strain, and ultimate stress-strain (for nonlinear finite element analyses) must be accurately defined; conservative nominal values frequently used in traditional design methods must be replaced with expected or "best estimate" characteristics that will be expected in the particular detail.

5) defining boundary conditions - the boundary condition restraints and/or loadings must be accurately determined from a "global" structural analysis. the loadings must be properly defined and include all of the important sources of imposed or induced stresses and strains; the global "coarse" structural analysis must have appropriate elements as previously discussed and there must be adequate detail of these elements in the vicinity of the fine mesh finite element analysis detail to permit accurate determination of the boundary conditions and loadings.

Errors that occur in FEA of CSD are not as straightforward as they may seem, due to the complex nature of FEA. Without a thorough training in FEA and a good feel for the structure being modeled, errors can be very difficult to recognize. Organizations can likewise make errors in FEA usage. Insufficient FEA training, guidelines for FEA usage, and verification and checking techniques for FEA models are all examples of organizational error. QA / QC measures can be instigated to correct these errors.

The problems inherent in computer design, and FEA in particular, are outlined in the following sections. A general analysis of FEA is then performed, using a generic organization typical of modern design and analysis organizations. This organization is then re-configured with new standards and QA / QC measures and analyzed again.

Risks of Automated Design

There are several general problems associated with highly automated design, some of which are outlined here. Although they are not examined in detail, they provide a valuable background for understanding some of the potential problems of specific applications such as FEA.

The finite element method, as well as other computer design applications, allows engineers to economically design and analyze structures that are much more complex than previously possible. However, this ability does not come without its associated risks. Using computer techniques for design and analysis has several inherent problems. It may also bring about new risks because of its abilities. This is both an individual and organizational issue. An individual must be aware of the limits of the application, and the organization must be willing to adequately train all users and must not promote the tool as a panacea for all design problems.

Petroski [1985] points out many of the possible problems arising from the use of computers in design of structures. Some of these are detailed in this section. Perrow [1984] discusses the phenomenon of "radar-assisted collisions", an example of how improved technology can lead to lower safety and control. This topic is presented as a loose analogy to FEA and to illustrate how reliance on new technology can be harmful. Knoll [1986] pointed out:

> *"The computer is the ultimate fool and we have elevated it to the ultimate authority. What is going to be the price?"*

Computer Optimization. Complex structures historically have been intentionally over designed. This was done because design iteration was simply too time-consuming to carry out by hand, due to the many complicated calculations involved. Computer design and analysis of structures has changed this. Now design iteration is possible and all aspects of a structure can be optimized for the lowest required capacity to minimize cost, weight or another key characteristic.

This can lead to problems in several ways. The safety factors being used in the designs are based upon experience with the over designed structures, and may be low for thoroughly optimized structures. This can result in failures which would have been avoided without computer optimization. The optimized structures will also tend to be less robust, having more weak links, which also makes them more susceptible to failure.

Computer Reliance. Engineers using computers extensively tend to lose a feel for the behavior of the structure. They tend to believe implicitly in computer answers. This is due in part to the accuracy reported in computer answers, which is almost never a reflection of the accuracy of the input data.

A good sense of the structure in question will always be necessary to engineers. Computer applications fall short of being able to carry out a complete design or analysis by themselves. It is still necessary for an engineer to be able to identify the various failure modes which he believes a structure may be subject to. Computers cannot be used for design, as they still cannot compute all of the available options available in a design, so engineers must remain capable of using their judgment.

Verification. Possibly the greatest problem in computer design, FEA in particular, is the fact that structures tend to be so complex that they can not be

easily verified by engineers using hand calculations. Even simple FEA models of details tend to have hundreds or even thousands of elements, which is far too many for hand calculation checking. This means that an engineer must rely on simple calculation methods, such as a basic beam analysis, to determine whether or not answers are of the correct order of magnitude. There is no means to verify specific stress values in a structure short of model and prototype testing.

Therefore, it is critical that engineers be capable of using good judgment when interpreting computer output. An analysis may be carried out using reasonable techniques, without triggering any alarms, and still contain incorrect answers by means shortcomings in the application. If an engineer does not have an intuitive feel for what values are reasonable, he will not be likely to catch these errors.

Technology Reliance. Perrow [1984] describes a phenomenon of technology-reliance : "radar-assisted collisions" in marine traffic. Radar was meant to solve the problem of marine collisions in the simplest manner possible : allow the crew of a ship to accurately "see" their surroundings, and thereby avoid collisions with nearby ships, bridges, shore, etc. Radar was quite proficient at identifying these dangers. However, the collision rate did not go down with the advent of radar.

Why did improved "sight" not lead to a lowering of collisions? Because the gain in vision was used to increase speed, not as an anti-collision measure. Vessels previously proceeded slowly when they were nearly sightless, but with radar, they could make full speed. This worked well as long as their radar was in good operation and no other ships with radar were in the vicinity. However, once radar became common, it was difficult to anticipate what course another vessel would take based on its own interpretations of its surroundings. Radar also failed to reduce accident rates because it was a fairly complicated tool to operate, and was not a universal answer to collision avoidance, as most people believed it to be. Finally, radar incorporates some automated features, such as "closest point of approach", which can be fooled and incorrectly interpreted. Features like this, when incorrectly interpreted, led to "non-collision course collisions" and "radar-assisted collisions".

Obviously, radar is not a direct analogy to FEA. However, FEA was developed as a tool to understand the behavior of a structure, and is being used to minimize weight and cost by reducing strength to minimum necessary levels. It is also a fairly complicated tool to operate, with features which are not always correctly interpreted. It is also viewed at times as a universal answer to structural behavior, although it often falls short in several ways.

Common FEA Errors

The author conducted interviews with users of FEA packages and combined this information with existing literature to identify some common errors which arise from the use of FEA in ship CSD. These errors are not specific to a particular FEA package. The errors arise because of the variations in modeling techniques, the differences between finite element models and real three-dimensional strttctures, and the problems inherent in checking complex computer calculations.

Some of these problems could be lessened by definitive guidelines in the use of FEA. However, it is difficult to define a "fixed" procedure that gives consistent results for CSD. Initial comparisons of fatigue lives have differed by factors of 10 to over 50 depending upon application and usage]Bea, 1993].

In a study conducted under the auspices of the International Ship and Offshore Structures Congress (ISSC) the results from FEA of the transverse frame of a 350,0000 DWT tanker have been reported [Ziliotto, 1991]. The transverse frame drawings and loading conditions were supplied to nine FEA experts. These experts performed the FEA of the transverse frame and then compared the results.

The maximum bending moments determined at the bottom transverse in the wing tank differed by a factor in excess of 4. The normal force in the transverse frame strut differed by a factor in excess of 2. The axial stress in the flange of the bracket between the bottom transverse and the longitudinal bulkhead differed by 40 %. These differences were due to differences in the assumptions made in defining the FEA models)mesh, boundary conditions, types of elements) and in differences in the FEA solution procedures. The definition of boundary conditions was the assumption that had the largest affect on the results [Ziliotto, et al., 1991].

A similar and later study of FEA of the ship global structure and local FEA CSD has been reported by Sumi, et al. [1994]. This study, performed under the auspices of the ISSC, involved two stages of FEA of a CSD in an 88,000 DWT tanker performed by eleven FEA experts. The first phase was intended to define the boundary and loading conditions of the CSD. The second phase was intended to define the local hot spot stresses. Loading conditions were specified, but the assumptions and performance of the global and local FEA left to the experts.

The first phase results indicated the critical stresses at the boundaries of the CSD studied differed by factors in the range of 2.1 to 3.6 The Coefficient of Variation in the first phase results ranged from 23 % to 35 %.

The second phase results indicated hot spot stresses that differed by factors in the range of 1.6 to 2.0. The Coefficient of Variation in the second phase results franged from 15 % to 20 %.

In the Phase 1 analyses, the principal sources of the differences were identified as the structural idealization in the vicinity of the supported boundaries, and the element types and mesh subdivisions used in the analyses. In the Phase 2 analyses, the deformation modes applied on the boundaries of the local CSD, the types of elements, and again the mesh types and subdivisions.

It was noted that the accuracy of the stress values at the hot spots could be improved by using an adaptive meshing technique which is available in some commercial codes [Sumi, 1994]. This recommendation has been used by Ma and Bea [1994] in a recent study of hot spot stresses in CSD. The adaptive meshing technique integrated into the FEA code was utilized in this study. A major problem with mesh incompatibility was identified and eventually solved. The mesh incompatibility had major influences on the FEA hot spot stresses. This is a problem for verification of the FEA code which itself can contain significant error inducing routines or capabilities [Thompson, 1993].

Mesh Incompatibility. For results to be accurate, the mesh of a finite element model must be compatible from element to element. Where discontinuities in the mesh exist, there are likely to be discontinuities in the stress distribution, which can affect an entire analysis, even when the incompatibility occurs in a low stress area, far away from the point of interest.

The problem in mesh compatibility arises because it is necessary to define "fine" mesh over the area of interest and "coarse" mesh elsewhere. Coarse mesh must be used to reduce computing time to reasonable levels, while fine mesh must be used to obtain a sufficiently detailed analysis of the hot spot area. The problems of mesh compatibility arise in the areas where coarse mesh and fine mesh border. An intermediate mesh is required in these areas. This intermediate mesh supplies connectivity between the fine and coarse mesh nodes so that the stresses and strains determined at these nodes are correctly interfaced. This concept is illustrated in Figure 9.41.

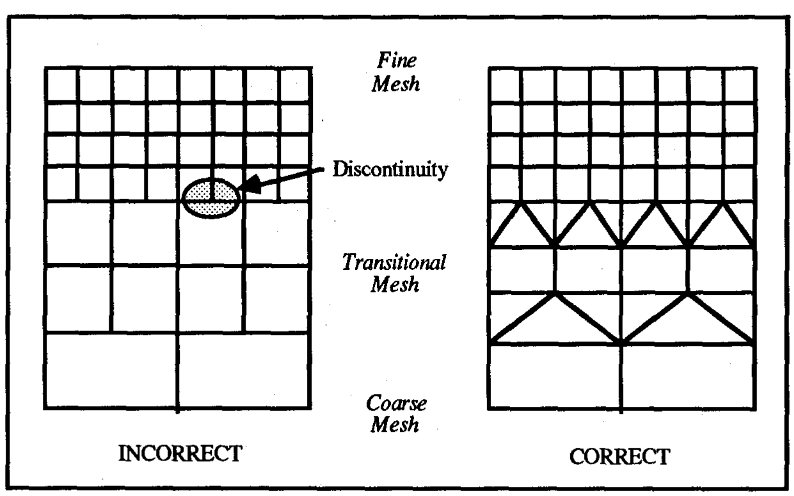

Figure 9.41 - Automated adaptive meshing (incorrect) and correct mesh connectivity

Incorrect mesh connectivity is very difficult to detect. Most programs do not have a feature which can detect this type of problem, so incorrect results are returned without warning. Therefore, it is up to the user to visually examine the model for mesh incompatibility. This can be very difficult and time consuming in a complex three-dimensional model. This problem is also inherent in the automatic mesh sizing features of some programs, making it more difficult to detect. Training, attention to detail, care, and provision of incentives to "be accurate" are critical in preventing errors of this type.

Realistic Modeling. Current FEA packages fall short of perfectly realistic modeling in several ways. FEA programs seek to model three dimensional structures with one and two dimensional elements. This is done because three dimensional elements would require enough nodes to slow down FEA applications to the point of being uneconomical. The use of one dimensional and two dimensional models has drawbacks and risks, however.

Using two dimensional elements can result in a model that accurately represents most aspects of a ship structure. However, some aspects cannot be accurately modeled. Elements which overlap other elements, for example, cannot be accurately modeled. This is a problem in modeling CSD, as "locks" are usually used. These locks are plates which overlap gaps in the CSD.

Another problem in the use of one and two dimensional analysis is the degree of accuracy obtained. It is very difficult to determine how well a non-three dimensional element models the behavior of a three dimensional element, as testing is not possible. It is also difficult for most engineers to anticipate how a one or two dimensional element will behave. This means that errors in the modeling are more difficult to detect.

A related shortcoming of FEA in CSD modeling is the problem of modeling welds and other non-standard shapes. It is relatively easy to model plates and beams accurately, but welds are a different matter. Welds will have individual shapes and be of varying quality, as they are products of hand workmanship.

Welding also introduce residual stresses which are extremely difficult to quantify, as well as being of indeterminate consistency. Residual stresses are present in all welded structures. Residual stresses can be local to the weld and global to the structural system. The global system residual stresses will be highly dependent on the assembly, welding, and any pre-heating procedures. The residual stresses can be at or close to yield in large areas of the structure and CSD. Given additional loading, plastic strains are developed which can dramatically affect the distribution of stresses.

All of these issues are a problem in FEA (most of which presume linear material behavior) because the geometry, residual stresses, material yield, and material consistency of the welded material are not considered when stress concentrations are calculated in these areas. These limitations in FEA

modeling puts a serious limitation on the accuracy which can be obtained in FEA.

It is for these reasons that in industries that have developed very advanced FEA capabilities, such as the commercial airframe industry, do not "believe" results from FEA until they have been calibrated and verified with small specimen testing and large assembly testing [Bea, 1993]. Extensive laboratory and prototype testing provides the essential ingredient to being able to use FEA in the design of commercial and combatant airframes.

Element Sizing. The choice of relative element size can have an effect on the stresses obtained in analysis. This is due to the averaging effects of the finite element method, as illustrated in Figure 9.42. Smaller elements will tend to give higher stresses than larger elements in the same area in regions where stress increase with proximity to a discontinuity, such as a joint or angle. The average stress for an element is indicated by a dotted line. It can be seen that smaller elements will give higher stresses. Therefore, the engineer using FEA must be aware of this problem and have an intuitive feel for what a reasonable stress level in the given type of detail would be. An engineer not familiar with this effect may not realize that stress concentrations are high if large elements are used, and may believe stresses are deceptively high if small elements are used.

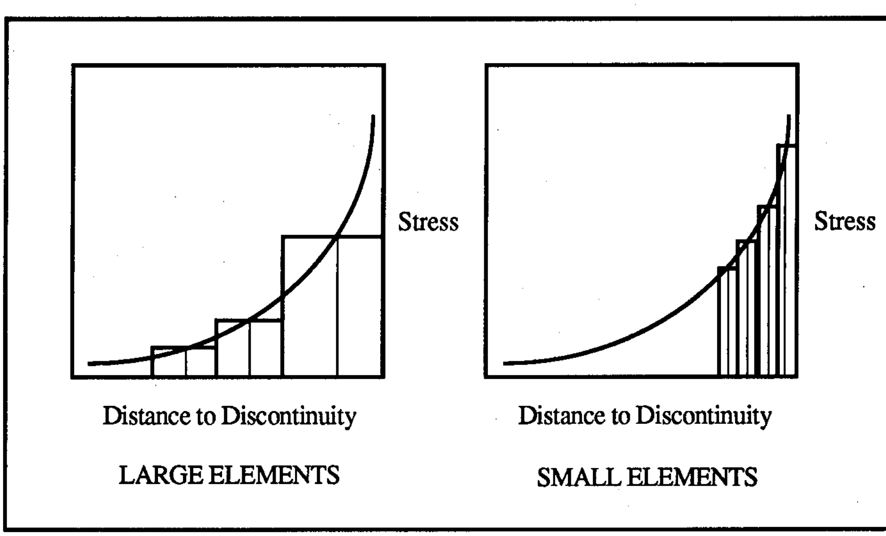

Figure 9.42 - Hot spot extrapolation stress levels and element sizes

Linear Analysis. Most FEA packages use linear approximations of the stress-strain relationship for materials. As discussed earlier in this section, this means that plastic deformation is not considered. This can lead to infinite stress concentrations at singularities. This problem must be treated in the same manner as mesh sizing : the engineer must be aware of the phenomenon to recognize it, and must have a feel for what the true stress value in the area would be.

Quality Profile For FEA of CSD

In order to apply a quality profile to a portion of a ship structure design analysis such as FEA of CSD, it was necessary to develop a quality profile for a design analysis tool. This required identifying the properties of an analysis tool which indicate high or low quality and reliability. A list of characteristics indicative of the quality of analysis tools is given in Table 9.6.

Table 9.6 - FEA of CSD analysis quality profiling characteristics

Accuracy / Correctness
Consistency
Input Practicality
Output Clarity
Compatibility / Simplicity
Intuitive Verification
First Principles Verification
Empirical Verification
Procedures Organization / Documentation

Accuracy refers to how well the tool represents the actual structure and its behavior. Correctness refers to the lack of faults or flaws in the procedures. Consistency refers to the repeatability of results for similar problems with different users.

Input Practicality refers to the ease of use of the tool and how difficult or simple it is to model a structure or process. It also refers to the availability of input data. Output refers to the clarity of the answers given by the tool and whether problems are made evident.

Compatibility refers to the ability of the design procedure to be readily integrated into common engineering and naval architecture procedures. Simplicity refers to the degree of complication, intricacy, and difficulty of understanding and using in the context of common engineering and naval architecture procedures.

Intuitive Verification refers to the ability of a user to tell whether answers appear reasonable or not by experience and general scientific knowledge. First Principles Verification refers to the ability of a user to check the accuracy of results by independent and / or "hand" calculations. Empirical Verification refers to the ability to check the results given by the tool by model or full-scale testing.

Procedures organization and documentation refer to the practicality and clarity of the written procedures, the detail and correctness of their documentation and the effectiveness of the information transmission contained in the written procedures.

A tool which has high marks for all of these attributes should give high quality results, as users will understand its workings and recognize any problems, as well as knowing how accurately the tool represents reality. A tool with an indicated low quality is likely to produce designs with undetected problems.

Evaluation of Quality Profile for Example FEA

A quality profile for the example FEA of the example CSD is given in Figure 9.43.

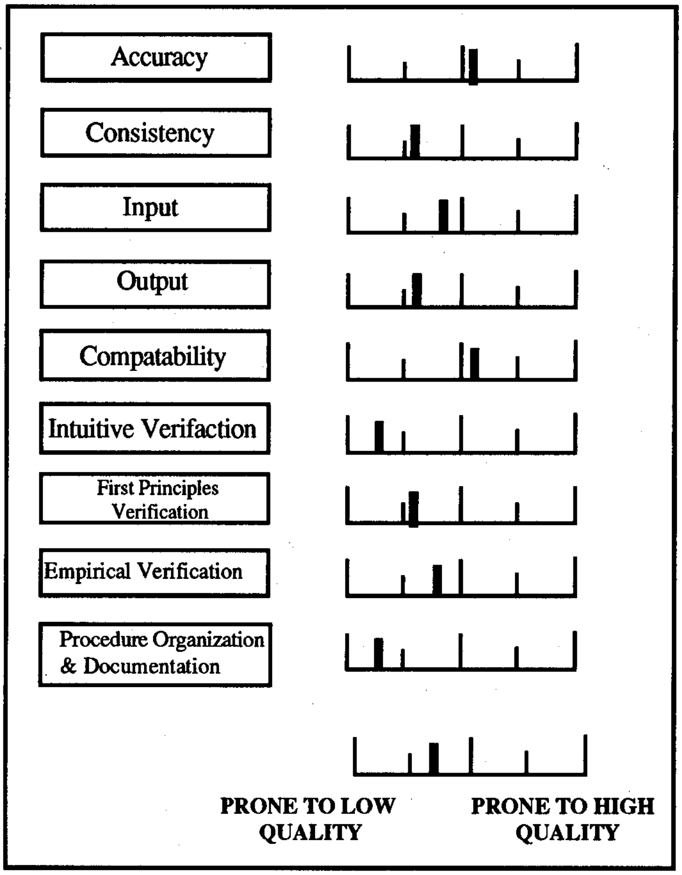

Figure 9.43 - Quality Profile for example FEA of example CSD

FEA is given an average score for accuracy. Although FEA can be very accurate for plates and simple structures, it loses accuracy when welds and other odd features must be included. Its accuracy is also somewhat deceptive, as it (like most computer applications) reports many more significant digits than is reasonable based on the uncertainties and approximations involved.

Consistency is given a low score because of the high dependence on mesh sizing, which is a function of user judgment and will vary widely with different users.

Input is given a low score because some important points in input are often glossed over in FEA packages, particularly mesh sizing, shortcomings of non-three dimensional elements and the effect of welds. Output is given a low score because output is often too complex to check thoroughly, resulting in users "drowning in numbers". Problems can easily go unnoticed. Finally, FEA will not identify all failure modes.

Compatibility / Simplicity is given an average score because the FEA are merged reasonably with common engineering procedures.

Intuitive Verification is given a low score because users do not have a feel for how a one- or two-dimensional structure will behave. Users are also probably ignorant of exact stress values in details.

First Principles Verification is given a low score because it is nearly impossible to check even a small section of a structure by hand, as boundary conditions are not known. Simple beam analysis is usually the best method of checking available, and this gives only an order of magnitude comparison.

Empirical Verification is given a low score because actual testing would require a full-scale model and a very large number of strain gauges. Such testing was not done, and in general, is a rarity in this industry [Schulte-Strathaus, 1993].

Documentation is given a low score because of the absence of definitive guidelines and procedures to perform FEA of CSD. The example FEA computer program documentation is a "nightmare." Unnecessary complexity and incorrectness in the documentation abound.

The overall Quality Profile of the example FEA of the example CSD is that it may pass designs with undetected quality problems.

Example 2 - Quantitative Analysis

The example FEA of the example CSD is examined in a similar fashion to the first example, although the sequence of EDA is different. The example is divided into four categories of HOE. These categories and their components are summarized in Table 9.7.

Errors in mesh compatibility are judged to be the product of ignorance (users who do not understand how to correctly form the mesh to pick up stress concentrations) and slips (users who accidentally define a mesh with discontinuities).

Table 9.7 - HOE factors in example FEA of CSD

I. MESH COMPATIBILITY
Human Error, Ignorance
Human Error, Slips
II. REALISTIC MODELING
Organizational Error, Ignorance
III. ELEMENT SIZING
Human Error, Ignorance
Human Error, Selection and Training
IV. LINEAR ANALYSIS
Human Error, Ignorance
Human Error, Selection and Training

Realistic modeling errors are expected to be due to organizational ignorance (organizations which do not realize the approximations and assumptions implicit in modern FEA, including dimensionality and welds, and promote it as a universal tool for design problems).

Element sizing errors are expected to be due to ignorance (users who do not understand how to properly size for relevant concentrations) and selection and training (users who can not recognize a reasonable or unreasonable stress concentration).

Errors due to linear analysis factors are also considered to be errors of ignorance (users who are unaware of the shortcomings of the specific FEA package in approximating the stress-strain relationship) and selection and training (users whose background does not give them a feel for what reasonable values are and what the implications of a linear approximation of the stress-strain relationship can be).

Quantitative Analysis - Original System

A baseline error rate must be established for each factor in the example. All of the errors are ones that should not occur with good vigilance, but may be expected to occur under normal conditions. These errors fit the category of "Errors of commission such as operating the wrong button or reading the wrong display" [Rettedal, et al, 1994; Williams, 1988], and therefore have been assigned a likelihood of 10^{-3} (for the FEA of the CSD design phase).

Errors in realistic modeling, an organizational error, are difficult to assign a base rate to. Organizational errors are difficult to assign rates in general, because the data simply is not available. However, the problem in realistic modeling seems to be less severe than the fatigue analysis organizational error in example 1 which was given a base error rate of 10^{-2}, so the use of 10^{-3} is internally consistent. It should be remembered that all of the baseline error rates are approximations, and cover a range of values.

As in example 1, the probabilities of situations to induce errors being present are divided equally in this segment of the analysis, and are altered in the analysis of the system when re-configured, based on the effect of new QA / QC measures, as described.

The four factors are examined in the ETA - FTA summarized in Figure 9.44 through 9.47.

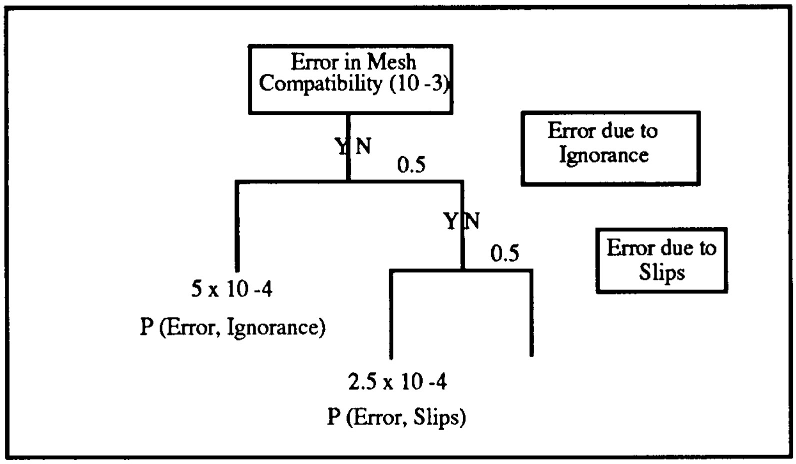

Figure 9.44: Factor I analysis

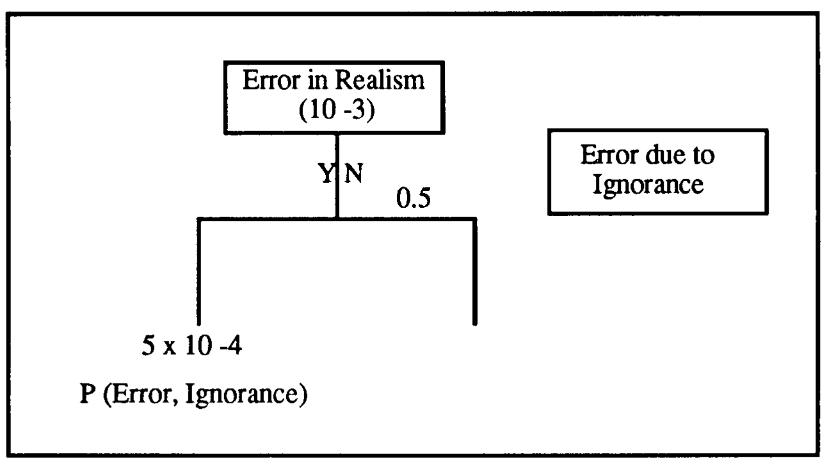

Figure 9.45 - Factor II analysis

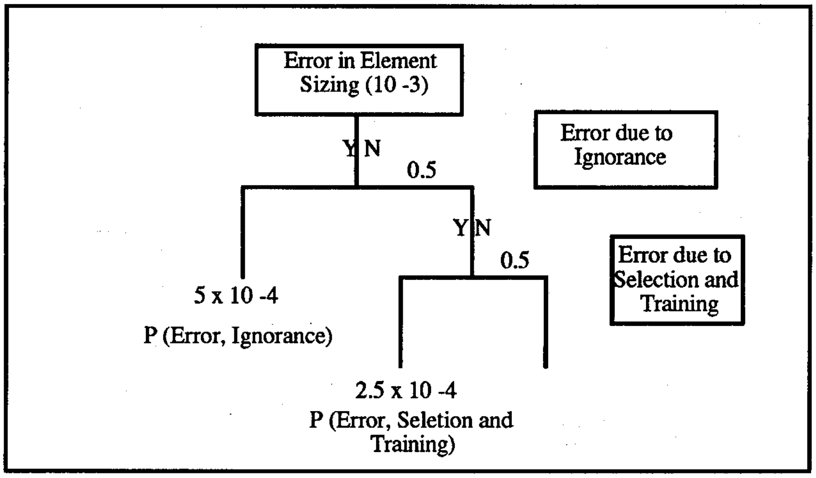

Figure 9.46 - Factor III analysis

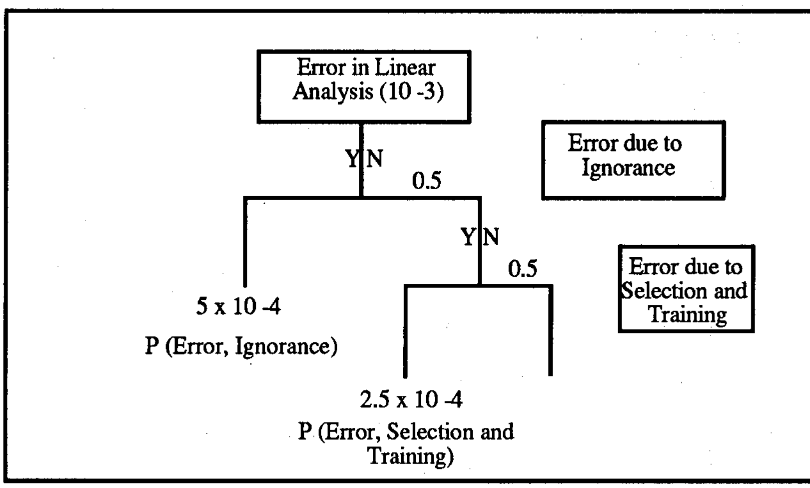

Figure 9.47 - Factor IV analysis

Quantitative Analysis - Re-configured System

The reconfiguration of the system to reduce the likelihood of errors in FEA is based on two measures : increased QA / QC and an organizational change in view of FEA. These measures are described for each factor in this section, and are evaluated in the following section.

Factor I can be improved chiefly by concentration on training in the proper usage of FEA. When users understand the issues involved in defining mesh -- the problems of discontinuities, the calculation time involved in coarse mesh, etc. -- they will be much less likely to create a model with mesh problems, as well as being more likely to catch errors in mesh in existing models. Defining a standard method for mesh creation would have a very good effect on

consistency. It would also improve the effectiveness of checking, as all users would be basing their mesh on the same principles. Development of standard practices may not be easy, but it is of great value in improving quality.

Changes in Factor II would rely on an organization-wide change of view of FEA. The shortcomings of FEA in modeling physical structures and behavior must be realized and incorporated into the use of FEA. Complete reliance on FEA is unreasonable, and the organization must present this attitude to the users of FEA. Making this change in stance will be difficult, but could be part of the increased training effort required in work on the other factors.

Factor III would be improved by QA / QC focus on teaching FEA users the shortcomings of FEA in representing details, particularly the relation between element size and stress concentration values. Users would also benefit from a background on what are reasonable values and what are not. Standard guidelines would be very helpful in reducing this problem, as guidelines could detail how mesh should be handled in areas of importance where stress concentrations may be affected by element sizing.

Factor IV would be best handled in the same manner as Factor III, by a concentration on teaching users what linear analysis problems look like and how they can be recognized, avoided or circumvented.

The system is now analyzed with the reconfiguration suggestions made in the previous section. The probabilities of occurrence have been changed, while the baseline error rates have remained the same.

Factor I has been improved by a QA / QC focus on training in FEA mesh definition (Figure 9.48). Users will be much less likely to define problematic mesh, either by ignorance or mistake, and will also be more likely to catch errors in mesh definition.

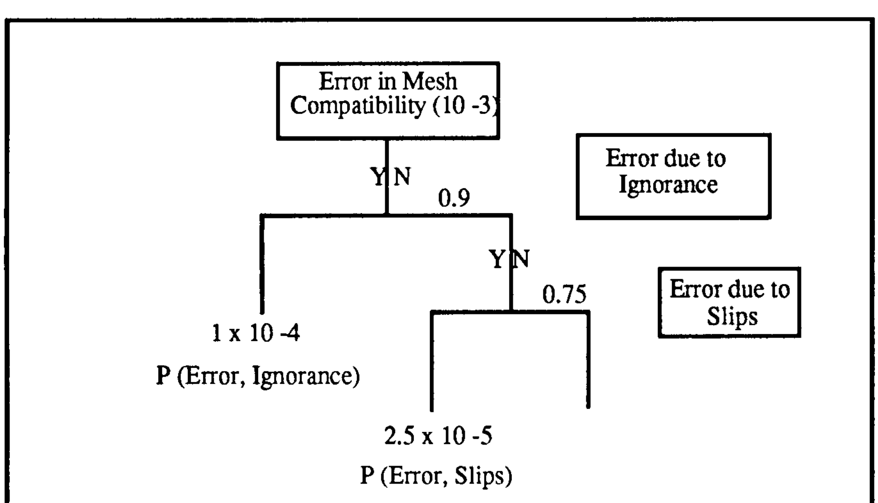

Figure 9.48 - Factor I system evaluation

Factor II would experience improvement through a design organization-wide education and training in the proper use and application of FEA (Figure 9.49). Once the approximations and assumptions inherent in FEA are widely known, users will be less likely to rely on it completely, and more verification will be done, thereby lowering the likelihood of errors in realistic modeling.

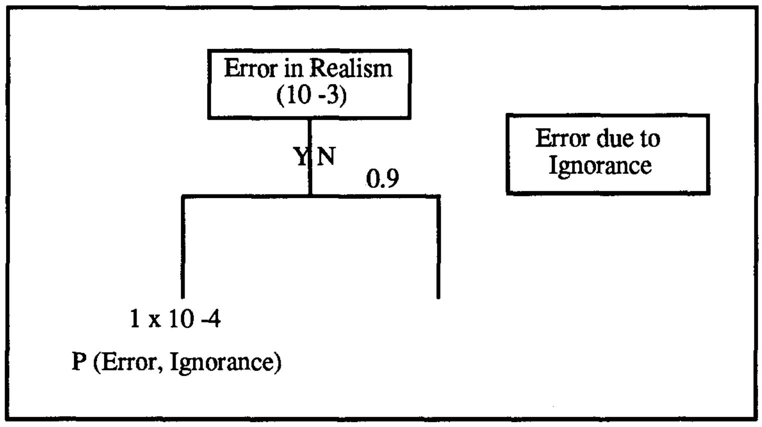

Figure 9.49 - Factor II re-configured system evaluation

Factor III would be improved by QA / QC efforts focusing on proper element sizing of details and a set of established guidelines for FEA usage (Figure 9.50). An effort in hiring QA / QC to focus on engineers knowledgeable in first principles would also reduce error probabilities, as misleading stress concentrations could be recognized.

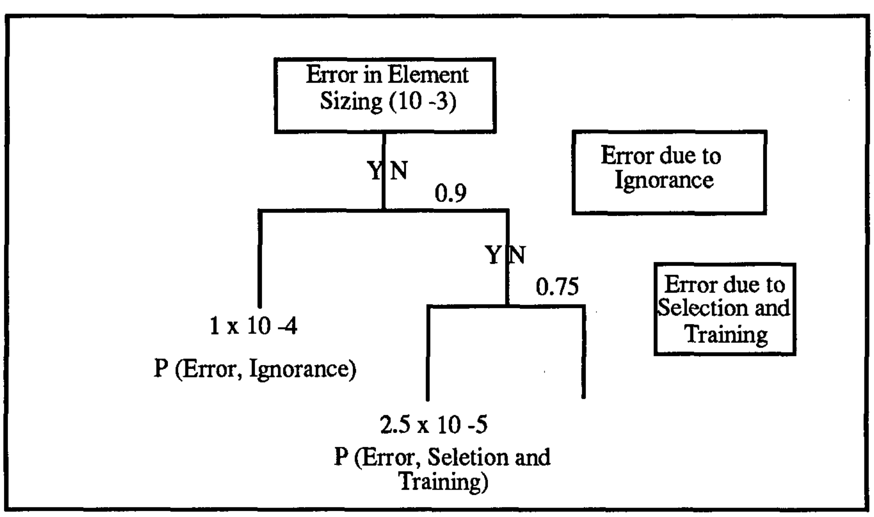

Figure 9.50 - Factor III re-configured system evaluation

Factor IV would benefit in the same ways as Factor III from improved QA / QC efforts in training and hiring, as well as from standard FEA usage guidelines (Figure 9.51).

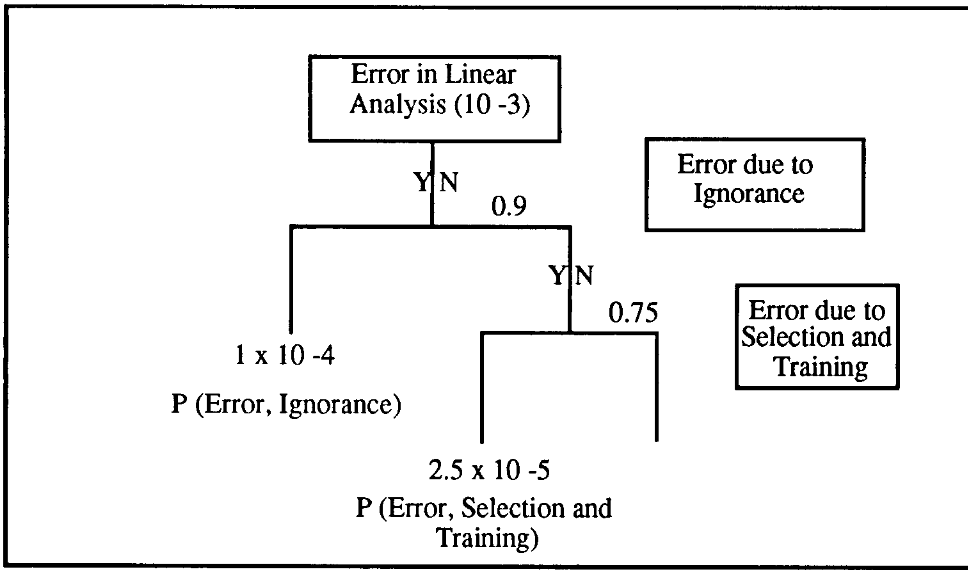

Figure 9.51 - Factor IV re-configured system evaluation

Observations - Quantitative Analysis

Table 9.8 summarizes the results from the original and revised system evaluations. In the original FEA design system, each of the four categories of HOE have about the same likelihood of occurrence. In the original system, the total probability of an significant error in the FEA during the design of the CSD is equal to 3 E-3.

Each of the four HOE factors can be substantially improved by the use of QA / QC measures and design organizational training in the applications and limitations of FEA. The reduction in error likelihood achievable with each of the improvements in the re-configured FEA system is identified in Table 9.8. After the design FEA system reconfiguration and improvements, the probability of a significant error in the FEA during the design of the CSD is equal to 5 E-4. The improvements in the FEA CSD design system result in about an 80 % reduction in the likelihood of a major error.

Factor II would probably be the most important element to concentrate improvement efforts on, as it has the widest-reaching effects. Concentrating QA / QC efforts on training in the proper use of FEA, establishing clear guidelines for FEA usage, and changing the organizational stance towards FEA usage would lessen the probability of an error occurring in FEA use.

Table 9.8 - Summary of results from Example 2

FACTOR I : MESH COMPATIBILITY		
Baseline Error Rate	*1.00E-03*	
	As Configured	As Re-configured
P Ignorance	*0.50*	*0.10*
P Slips	*0.50*	*0.25*
P Error - Ignorance	5.00E-04	1.00E-04
P Error - Slips	2.50E-04	2.50E-05
Total P Error	7.50E-04	1.25E-04
Net Change		**83%**
FACTOR II : DIMENSIONALITY		
Baseline Error Rate	*1.00E-03*	
	As Configured	As Re-configured
P Ignorance	*0.50*	*0.10*
P Error - Ignorance	5.00E-04	1.00E-04
Total P Error	5.00E-04	1.00E-04
Net Change		**80%**
FACTOR III : ELEMENT SIZING		
Baseline Error Rate	*1.00E-03*	
	As Configured	As Re-configured
P Ignorance	*0.50*	*0.10*
P Selection and Training	*0.50*	*0.25*
P Error - Ignorance	5.00E-04	1.00E-04
P Error - Selection	2.50E-04	2.50E-05
Total P Error	7.50E-04	1.25E-04
Net Change		**83%**
FACTOR IV : LINEAR ANALYSIS		
Baseline Error Rate	*1.00E-03*	
	As Configured	As Re-configured
P Ignorance	*0.50*	*0.10*
P Selection and Training	*0.50*	*0.25*
P Error - Ignorance	5.00E-04	1.00E-04
P Error - Selection	2.50E-04	2.50E-05
Total P Error	7.50E-04	1.25E-04
Net Change		**83%**

These results are consistent with those identified by the ISSC study cited earlier [Sumi, 1994]. The following quotation is from the Conclusions of that study:

> *"Some specific guidance on how and where stresses are to be calculated would improve consistency in results. This should be included in finite element guidelines. Results from this study are believed to be what is expected in current finite element analysis and point to a need for a more well defined unified approach for finite element analysis of ship structures. This is particularly*

important when the consequences of differences in stress are considered in fatigue analysis where the differences are multiplied several times."

Summary

This chapter has presented examples of qualitative and quantitative assessments of the quality characteristics associated with design of marine structures. Two of the examples have focused on design of CSD in commercial tankers.

The purpose of these examples has been to illustrate how HOE analyses can be performed to identify weak links and critical flaws in the design processes. The purpose of this identification is to then allow the assessment of how best to improve the processes so that the desired quality / reliability is achieved.

The purpose of these analyses is to produce insights in how quality in ship structures might best be improved and to promote communications among those responsible for the quality of ship structures. The purpose of the analyses is to encourage a comprehensive evaluation of the "system" including its human, organization, hardware, procedure, and environmental aspects.

The purpose of these analyses is not to produce numbers nor to promote paralysis by analysis. The purpose of these analyses is not to take power from those responsible for the quality of ship structures. Rather. it is to better empower them to improve the quality of ship structures how, where, and when it is needed. Results from the analyses are intended to help identify where and how best to use limited resources to improve quality.

The fundamental problem in improving quality is not knowing what to do. The fundamental problem is not doing what we know we should not do.

The next chapter in this report will summarize what has been learned during this project about how best to promote quality in the design of the ship structure, particularly as it is applied to the SSC reliability based ship design procedures development efforts.

Chapter 10

GUIDELINES FOR SHIP STRUCTURE DESIGN

Introduction

The objective of this chapter is to summarize the previous developments documented in this report in the form of general guidelines that can be used to improve the quality of ship structures during the design process. The guidelines are focused human error control and management before and during the design process. The objective of this control and management is to help assure that a defined level of quality is achieved with a given reliability.

These guidelines are cast in the framework of development of a new ship structure design process that is based on a Loading and Resistance Factor Design (LRFD) format [Mansour, et al. 1993]. The ship structure LRFD guidelines are being developed under the auspices of the SSC as part of a long-term research and development effort.

Overview

This project has identified five primary interactive and related components that are involved in the human factor related aspects of achieving acceptable quality in design of ship structures (Figure 10.1):

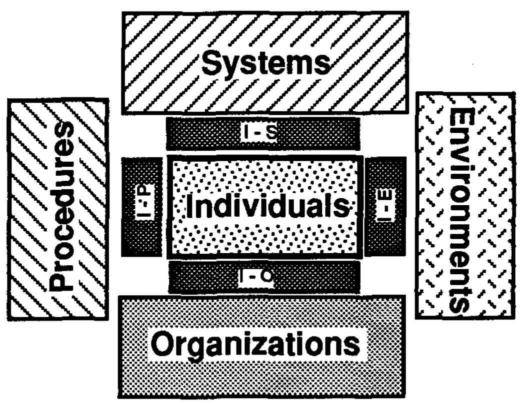

Figure 10.1 - Human performance factors

1) *individuals (members of the design team),*
2) *organizations (functional and administrative structures),*
3) *procedures (ways of doing things),*
4) *systems / hardware (physical equipment, facilities, structures), and*
5) *environments (complex of climatic and biotic factors; aggregate of social and cultural conditions).*

Reason [1990] suggested that latent problems with insufficient quality (failures, accidents) in technical systems are similar to diseases in the human body:

> *"Latent failures in technical systems are analogous to resident pathogens in the human body which combine with local triggering factors (i.e., life stresses, toxic chemicals and the like) to overcome the immune system and produce disease. Like cancers and cardiovascular disorders, accidents in defended systems do not arise from single causes. They occur because of the adverse conjunction of several factors, each one necessary but not sufficient to breach the defenses. As in the case of the human body, all technical systems will have some pathogens lying dormant within them."*

Reason [1992] developed eight assertions regarding error tolerance in complex systems in the context of ships and aircraft:

1) The likelihood of an accident is a function of the number of pathogens within the system.
2) The more complex and opaque the system, the more pathogens it will contain.
3) Simpler, less well-defended systems need fewer pathogens to bring about an accident.
4) The higher a person's position within the decision-making structure of the organization, the greater is his or her potential for spawning pathogens.
5) Local pathogens or accident triggers are hard to anticipate.
6) Resident pathogens can be identified proactively, given adequate access and system knowledge.
7) Efforts directed at identifying and neutralizing pathogens are likely to have more safety benefits than those directed at minimizing active failures.
8) Establish diagnostic tests and signs, analogous to white cell counts and blood pressure, that give indications of the health or morbidity of a high hazard technical system.

During this project and during the six years of research that has been associated with this project, a large number of cases have been studied in detail in which errors made during and in the design of the marine structure lead to the "failure" (lower than desired quality) of the structure. Several of these case histories have been detailed in Chapters 6, 7, and 8. Table 10.1 summarizes the key "causes" of these failures.

The single dominant cause of structure design related failures has been errors committed, contributed, and / or compounded by the organizations that were involved in and with the designs. At the core of many of these organization based errors was a culture that did not promote quality in the design process. The culture and the organizations did not provide the incentives, values, standards, goals, resources, and controls that were required to achieve adequate quality.

Table 10.1 - Key causes of structure design related failures

- new or complex design guidelines and specifications
- new or unusual materials
- new or unusual types of loading
- new or unusual types of structures
- new or complex computer programs
- limited qualifications and experience of engineering personnel
- poor organization and management of engineering personnel
- insufficient research, development and testing background
- major extrapolations of past engineering experience
- poor financial climate, initial cost cutting
- poor quality incentives and quality control procedures
- insufficient time, materials, procedures, and hardware

Loss of corporate memory also has been involved in many cases of structure failures. The painful lessons of the past were lost and the lessons were repeated with generally even more painful results.

The second leading cause of structure failures is associated with the individuals that comprise the design team. Errors of omission and commission, violations (circumventions), mistakes, rejection of information, and incorrect transmission of information (communications) have been dominant causes of failures. Lack of adequate training, time, and teamwork or back-up (insufficient redundancy) has been responsible for not catching and correcting many of these errors.

The third leading cause of structure failures has been errors embedded in procedures. Traditional and established ways of doing things when applied to structures and systems that "push the envelope" have resulted in a multitude of structure failures. There are many cases where such errors have been embedded in design guidelines and codes and in computer software used in design. Newly developed, advanced, and frequently very complex design technology applied in development of design procedures and design of marine structures has not been sufficiently "debugged" and failures (compromises in quality) have resulted.

In general, designer hardware and designer environments have not played major roles in the majority of structure design failure cases. The application of modern building science and ergonomics in the work place have been responsible for this condition.

Based on the study of non-marine structure failures summarized in Chapter 5, it is obvious that the same types and ordering of factors have been involved in failures of onshore structures. The marine and the ship structure design fields are not unique in this aspect.

Another important concept has developed from these failure cases. This concept is that making the structures stronger or utilizing larger factors of safety in its design is not an effective or efficient way to achieve sufficient and desirable quality in the structures. Resources are best focused at the sources of the quality problem which in this case are the humans involved in the structure design activities.

This is not to say that one should not consider the human aspects directly in the structure design procedures and processes. Human errors will occur during design, construction, and operations. One key objective of the design process should be to make the ship structure so that it can better tolerate such errors and the defects and damage that it brings with it. This is design for "robustness." This is design to minimize the effects of inevitable human error (fault tolerance).

Another key objective of the design process should be to make the ship structure not invite or promote human errors. This is the development of design procedures and processes that will promote quality in the work to be performed by designers, constructors, and operators of ship structures (fault avoidance). The design process should promote detection and removal of errors throughout the life-cycle of the ship structure (fault detection and removal).

This insight indicates the priorities of where one should devote attention and resources if one is interested in improving and assuring sufficient quality in the design of ship structures:

1) organizations (administrative and functional structures),

2) individuals (the design team), and

3) procedures (the design processes and guidelines).

This ordering will form the outline for the remainder of this chapter.

Quality in Design Organizations

Even though it may be the most important, the organization aspects of ship structure design quality are perhaps the most difficult to define, evaluate, and modify. Because of their pervasive importance in determining the quality which is achieved in the design of ship structures, some critical aspects of quality in design organizations will be addressed in this section.

The ship structure design process should be viewed in the context of the multiplicity of organizations that influence the quality of that process. The organizations and their activities form a "mega-system" [Wenk, 1986] that should be recognized and addressed. These mega-systems and their organizational components must be understood as "organisms, living systems that relate to each other."

In Chapter 7, the section on Organization Responsibilities attempted to identify the major components of this mega-system and their associated responsibilities.

The implementation of TQM in design organizations is a current example of efforts directed at the organization aspects associated with design of ship structures. Chapter 2 of this report has summarized the foundations of TQM and defined how the ISO design Quality Standards can compliment the general efforts to achieve quality in design organizations.

Critical flaws to avoid in implementing these approaches is development of "minimum compliance mentalities" and making them an unnecessarily burdensome "paper chase".

Studies of HRO (High Reliability Organizations) [Roberts, et al., 1989-1994] has shed some light on the factors that contribute to risk mitigation in HRO [Roberts, 1992]. HRO are those organizations that have operated nearly "error free" over long periods of time. A variety of HRO ranging from the U. S. Navy nuclear aircraft carriers to the Federal Aviation Administration Air Traffic Control System have been studied.

The HRO research has been directed to define what these organizations do to reduce the probabilities of serious errors [Roberts, 1989]. Reduction in error occurrence is accomplished by the following:

1) command by exception or negation,
2) redundancy,
3) procedures and rules,
4) training,
5) appropriate rewards and punishment
6) the ability of management to "see the big picture".

Command by exception (management by exception) refers to management activity in which authority is pushed to the lower levels of the organization by managers who constantly monitor the behavior of their subordinates. Decision making responsibility is allowed to migrate to the persons with the most expertise to make the decision when unfamiliar situations arise (employee empowerment).

Redundancy involves people, procedures, and hardware. It involves numerous individuals who serve as redundant decision makers. There are multiple hardware components that will permit the system to function when one of the components fails.

Procedures that are correct, accurate, complete, well organized, well documented, and are not excessively complex are an important part of HRO. Adherence to the rules is emphasized as a way to prevent errors, unless the rules themselves contribute to error.

HRO develop constant and high quality programs of training. Training in the conduct of normal and abnormal activities is mandatory to avoid errors. Establishment of appropriate rewards and punishment that are consistent with the organizational goals is critical.

Lastly, Roberts [1992] defines HRO organizational structure as one that allows key decision makers to understand the big picture. These decision makers with the big picture perceive the important developing EDA, properly integrate them, and then develop high reliability responses.

In recent organizational research reported by Roberts and Libuser [1994], they analyzed five prominent failures including the Chernobyl nuclear power plant, the grounding of the Exxon Valdez, the Bhopal chemical plant gas leak, the mis-grinding of the Hubble Telescope mirror, and the explosion of the space shuttle Challenger. These failures were evaluated in the context of five hypotheses that defined "risk mitigating and non-risk mitigating" organizations. The failures provided support for the following five hypotheses.

> *1) Risk mitigating organizations will have extensive process auditing procedures.* Process auditing is an established system for ongoing checks designed to spot expected as well as unexpected safety problems. Safety drills would be included in this category as would be equipment testing. Follow ups on problems revealed in prior audits are a critical part of this function.

> *2) Risk mitigating organizations will have reward systems that encourage risk mitigating behavior on the part of the organization, its members, and constituents.* The reward system is the payoff that an individual or organization gets for behaving one way or another. It is concerned with reducing risky behavior.

3) Risk mitigating organizations will have quality standards that meet or exceed the referent standard of quality in the industry.

4) Risk mitigating organizations will correctly assess the risk associated with the given problem or situation. Two elements of risk perception are involved. One is whether or not there was any knowledge that risk existed at all. The second is if there was knowledge that risk existed, the extent to which it was acknowledged appropriately or minimized.

5) Risk mitigating organizations will have a strong command and control system consisting of five elements: a) migrating decision making, b) redundancy, c) rules and procedures, d) training, and e) senior management has the big picture.

In conclusion, the foregoing TQM, ISO, and HRO strategies and risk mitigating measures are intended to develop a level of ship structure design organizational quality and reliability that will be desirable and acceptable. Organizational trust and integrity are key aspects [Wilson, 1992]. These measures are intended to reduce the likelihoods of the categories of organizational errors identified in Figure 10.2 to acceptable and desirable levels. Responsibilities for implementation of these measures have been defined in Chapter 7 Table 7.5.

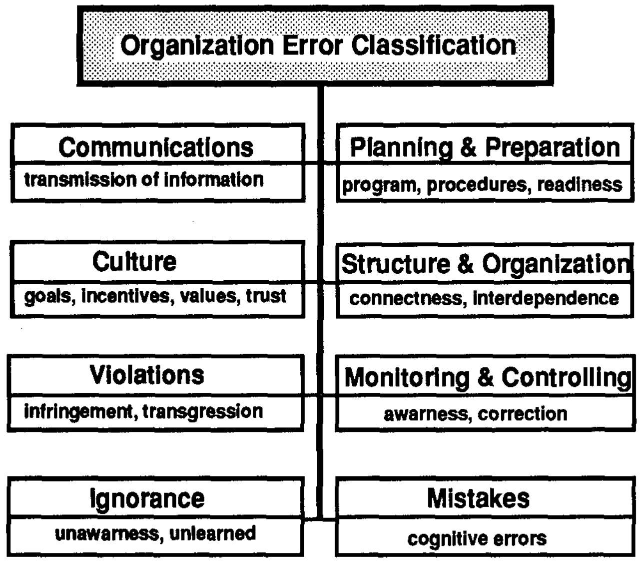

Figure 10.2 - Sources of organization errors

Quality in Design Teams

This section will address the activities of the individuals that are directly responsible for the design of ship structures. The activities of these individuals will be placed in the context of the structure design "team."

Errors on the part of the individuals have been classified into the eight categories identified in Figure 10.3. As indicated in Figure 10.4, these errors can potentially affect any or all of the five major components that comprise the ship design process. There are two primary lines of defense to prevent and / or detect and correct individual errors. The first line of defense is centered in the individuals performing the design analyses; the design team. The second line of defense is identified as QA / QC. These are activities of those outside the design team.

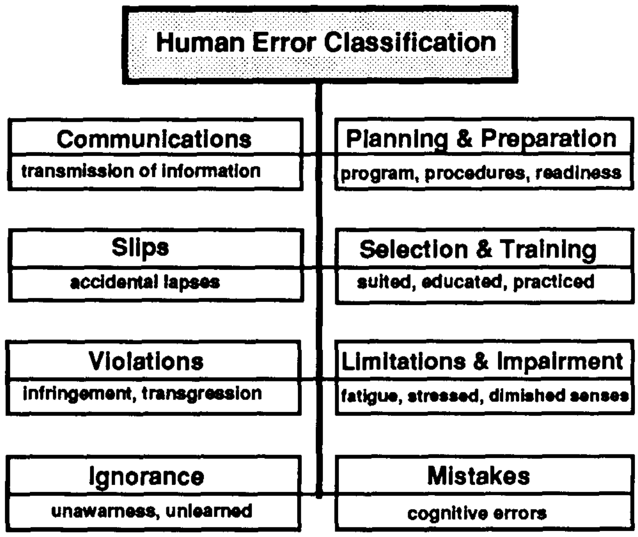

Figure 10.3 - Causes of individual human errors

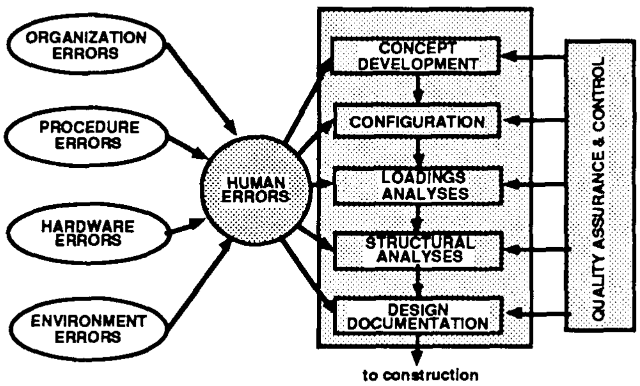

Figure 10.4 - Human factor influences in the ship structure design process

First Line of Defense

The first line of defense is associated with prevention and minimization of errors made and not corrected by the individuals that perform the design processes. The quality of the structural design is a direct function of the quality of the design team that performs the design. Table 10.2 summarizes the key factors that are need to be addressed to develop a high reliability ship structure design team. Many of these factors relate directly to the attributes of HRO and risk mitigating organizations.

Table 10.2 - Key factors in development of a high reliability ship structure design team

Communications Personnel selection Training Planning Preparations Discipline Quality resources	Procedures Organization Leadership Monitoring Information seeking, observations Controlling	Information evaluation Distributed decision making Appropriate operation strategies Quality incentives and rewards

Past problems associated with design of marine structures indicates that effective communications, personnel selection, training, provision adequate resources to achieve the desired quality, and provision of quality incentives and rewards are essential elements that determine the frequency and intensity of human factor related problems in structure design.

Communications has been identified as a major human factors problem in many other individual and team situations. The way in which information is presented, information distortion (biasing), and the formatting of the information can have dramatic affects on the effectiveness of the communications within the design team.

The two examples that addressed ship structure design problems clearly identified personnel selection and training as key issues. Personnel performance characteristics need to be matched to the job to be done. Attention to the details of normal and unique structural requirements is an essential performance characteristics needed in structural designers.

Training of design personnel must also match the job to be done. To enhance the performance of a specific task, the more repetition that occurs, then the lower the likelihood of error. To enhance problem solving, experience in a variety of tasks is needed.

Training of design personnel will be particularly important as an LRFD ship structure design process is implemented. There will be a loss of "feel" during the early phases of applying such a new design process. If errors are to be prevented or caught and corrected, this intuitive feel must be quickly reestablished in those that will apply the new guidelines.

Training of design personnel to understand the effects of biases and heuristics on their decisions is important. Decision makers involved in the design of complex structural systems need to be taught about confirmation bias; the tendency to seek new information that supports one's currently held belief and to ignore or minimize the importance of information that may support an alternative belief. Rigidities in perceptions, ignoring potentially criti-

cal flaws in complex situations, rejection of information, and minimizing the potentials for errors or flaws result from confirmation bias.

While not a panacea, the importance of continued and effective training of ship structure designers can not be over-emphasized, particularly as a new ship structure LRFD design guideline is implemented into practice.

A very important aspect of minimizing designer error regards team work. Team-work on the front lines of the design process can provide a large measure of internal QA / QC during these operations [Huey, Wickens, 1993]. Team-work can be responsible for interrupting potentially serious and compounding sequences of events that have not been anticipated. It is such team-work that is largely responsible for "near misses." And, it is for this reason that there are many more near misses than there are accidents.

As a result of his work on human errors in the design of non-marine structures, Melchers [1987] identified seven strategies that can be used to manage the occurrence and effects of such errors:

1) Education - on-the-job and continuing professional education.
2) Work Environment - open-minded goal-oriented.
3) Complexity reduction - simplification of complex design tasks.
4) Personnel selection - the skills and abilities of the team members must be appropriate for the type of design to be performed.
5) Self-checking - alertness to spot and correct significant errors made by the individuals performing the design process.
6) External-checking - provision of independent reviews to detect significant errors not detected by the design team.
7) Legal sanctions - deterrence or sanctions to inhibit negligence and deliberate malpractice (violations).

Addressing the last strategy, Melchers observed [1986]:

"There is evidence to suggest that sanctions may well be effective for premeditated crime but that in general the effect is likely to be most pronounced on those least likely to be involved. It is reasonable to suggest that few engineers premeditate to perpetrate errors, so that the most likely result of excessive threat of legal sanction is inefficiency, over-caution, and conservatism in the execution of work."

Second Line of Defense

QA / QC in structure design have been discussed in Chapter 7, evaluations of their effects discussed in Chapter 8, and illustrations of how they can improve the quality of marine structures developed in Chapter 9. Formalized methods of QA / QC take into account the need to develop the full range of quality attributes in the ship structure including serviceability, safety, durability,

and compatibility. These attributes have been defined and discussed in Chapters 1 and 2.

QA / QC measures are focused both on error prevention and error detection and correction. There can be a real danger in excessively formalized QA / QC processes. If not properly managed, they can lead to self-defeating generation of paperwork, waste of scarce resources that can be devoted to QA / QC, and a minimum compliance mentality.

In design, adequate QC (detection, correction) can play a vital role in assuring the desired quality is achieved in a marine structure. Independent, third-party verification, if properly directed and motivated, can be extremely valuable in disclosing embedded errors committed during the design process.

In many problems involving insufficient quality in marine structures, these embedded errors have been centered in fundamental assumptions regarding the design conditions and constraints and in the determination of loadings. These embedded errors can be institutionalized in the form of design codes, guidelines, and specifications.

It takes an experienced outside viewpoint to detect and then urge the correction of such embedded errors. The design organization must be such that identification of potential major problems is encouraged; the incentives and rewards for such detection need to be provided.

It is important to understand that adequate correction does not always follow detection of an important or significant error in design of a structure. Again, QA / QC processes need to adequately provide for correction after detection. Potential significant problems that can degrade the quality of a structure need to be recognized at the outset of the design process and measures provided to solve these problems if they occur.

Knoll's study of structure design errors and the effectiveness of QA / QC activities in detecting and correcting such errors lead to the checking strategies summarized in Table 10.3 [1986].

Table 10.3 - Design QA / QC Strategies

• WHAT TO CHECK ? - high likelihood of error parts (e.g. assumptions, loadings, documentation) - high consequence of error parts **• WHEN TO CHECK ?** - before design starts (verify process, qualify team) - during concept development - periodically during remainder of process - after design documentation completed	**• HOW TO CHECK ?** - direct toward the important parts of the structure (error intolerant) - be independent from circumstances which lead to generation of the design - use qualified and experienced engineers - provide sufficient QA / QC resources - assure constructability and IMR **• WHO TO CHECK ?** - the organizations most prone to errors - the design teams most prone to errors - the individuals most prone to errors

The structure design checking studies performed by Knoll [1986], the series of studies performed by Melchers and Stewart [1987-1990], and the studies performed during this project on marine structures indicate that there is one part of the design process that is particularly prone to errors committed by the design team. That part of the process is the one that deals with the definition of design loadings that are imposed on and induced in the structure. This recognition has several implications with regard to managing HOE in design.

The first implication regards the loading analysis procedures themselves. This implication will be further detailed and discussed in the next section of this chapter.

The second implication regards the education and training of structure design engineers in the development and performance of loading analyses. Given the complexities associated with performing loading analyses, the complexities associated with the loading processes and conditions, and the close coupling between the structure response and the loading environment, it is little wonder that loading analyses are probably the single largest source of structure design errors. What is somewhat disturbing is that many designers of marine structures do not understand these complexities nor have been taught how to properly address them in structure design.

Again, given the development of an LRFD ship design process that will involve new "loading factors" and new loading combinations associated with these factors [Mansour, Thayamballi, 1994], training of ship structure design engineers will be particularly important. This training requirement will be made even more critical as advanced Dynamic Loading Analyses (DLA) [Chen, et al., 1993] are implemented in very sophisticated computer based systems such as the ABS SafeHull System [Chen, et al., 1993]. The potential for "radar assisted collisions" cited in the previous chapter should be recognized and measures put in place to prevent such occurrences.

It is noteworthy that formalized procedures have been developed for the QA / QC process in software developments [Barnes, et al., 1993; ISO, 1987; Thompson, 1993; National Agency for Finite Elements and Standards, 1990]. These procedures need to be understood and implemented to avoid embedding serious flaws in ship design software.

The third implication regards the need for independent (of the situations that potentially create errors), third-party QA and QC "checking" measures that are an integral part of the ship structure design process. This checking should start with the basic tools (guidelines, codes, programs) of the structure design process to assure that "standardized errors" have not been embedded in the tools. The checking should extend through the major phases of the design process, with a particular attention given to the loading analysis portions of that process.

The intensity and extent of the design checking process needs to be matched to the particular design situation. Repetitive designs that have been adequately "tested" in operations to demonstrate that they have the requisite quality do not need to be verified and checked as closely as those that are "first-offs" and "new designs" that may push the boundaries of current technology.

Quality in Design Procedures

A specific objective of this project has been to address whether or not HOE should be reflected in structure design procedures and criteria. Specifically, this objective was directed at the development of a new LRFD procedure for ship structures.

A clear conclusion from this project is that HOE should be reflected in the new LRFD structure design procedures and criteria. This then leads to the question of how it should be reflected.

The results of this project indicates that there are three major ways in which considerations of HOE should be reflected in ship structure design procedures. The first two ways have been discussed in the preceding sections.

The third way is directed at helping achieve adequate and acceptable quality in the design procedures and processes themselves. The results from this project indicates that there are three strategies that should be considered:

- *Strategy 1* - QA / QC the design procedures and processes (fault avoidance),

- *Strategy 2* - QA / QC is integrated as a requirement directly in the design procedures and processes (fault detection and correction), and

- *Strategy 3* - Measures are introduced into the design procedures and processes that will minimize the effects of HOE on the quality of the ship structure (fault tolerance).

Strategy 1

In Chapter 3, several examples were developed to illustrate how errors that could lead to unacceptable or undesirable quality in ship structures could become embedded in the development of an LRFD guideline, or any guideline for that matter. The currently popular "calibration" approach to assure that LRFD and the "old" WSD procedures develop comparable or the same results does not assure that ship structure quality objectives are met. Rather, it implies that the same quality problems inherent in the old WSD procedure are translated into the LRFD procedure.

The author has participated for more than 25 years in the development of design guidelines for offshore platforms, including both WSD and LRFD developments in the U. S. and overseas. Development of a design code or guideline is no simple undertaking. Not only is complex technology involved, but as well complex organization and political issues are involved. In the struggle to develop the technical and organizational consensus that should be represented in a design code, technical completeness, correctness, and crispness can be compromised.

In one of these developments, an objective that was defined in the development of the LRFD guideline was to achieve "a more efficient structure" by balancing the reliabilities of the elements that comprised the structure. To the LRFD developers, it did not make sense that some components in the structure should have very low probabilities of failure while other components had much higher probabilities of failure. It was only after the need for damage and defect tolerance (robustness) in the structure was recognized, that the need for "unbalanced" design became apparent. This recognition not only influenced the design processes to assure adequate strength (capacity) in the structure, but as well its ductility and fatigue durability characteristics. Recognition of the needs for "fail-safe" design of the structures had major effects on the LRFD developments.

Current experience indicates that if not properly developed and documented, a design guideline can enhance the likelihood of significant errors being made by even experienced structural designers. These errors can lead to important compromises in the intended quality of the structure. The errors arise primarily because of the dramatically increased complexity of the design guideline, its similarly increased "opaqueness" (frequently caused by associated computer software), and the lack of sufficient training.

Research has shown that the difficulty of a particular task is influenced by five primary factors [Huey, Wickens, 1993]:

1) structure of the task,

2) task goals and performance criteria,

3) quality, format and modality of information,

4) cognitive processing required, and

5) characteristics of the input / output devices.

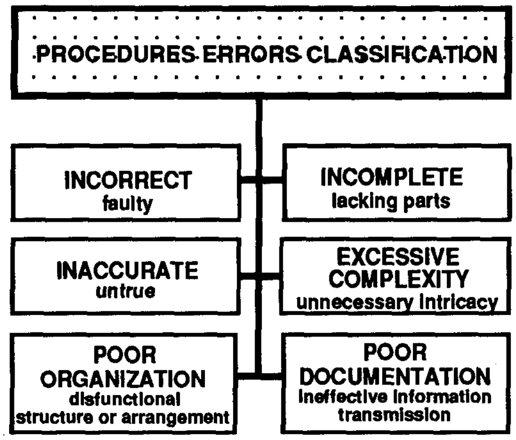

Figure 10.5 - Causes of errors in procedures

Table 10.4 - Structure analysis procedure quality characteristics

Accuracy / Correctness
Consistency
Input Practicality
Output Clarity
Compatibility / Simplicity
Intuitive Verification
First Principles Verification
Empirical Verification
Procedures Organization / Documentation

The more difficult a task is made, then the more likely that there will be errors. Those charged with development of ship structure design guidelines should be sensitized to these factors. Design guidelines should be developed that will minimize the difficulty of the tasks to be performed and thereby enhance the likelihood of high quality design results.

In the first strategy, the results of this project suggest that a thorough and independent, third-party QA / QC system should be defined and implemented during the development of an LRFD ship structure design procedure. The QA / QC process should parallel the development of the LRFD guidelines. Due to the importance of such a procedure, as much effort should be devoted to QA / QC as is devoted to the LRFD development itself.

This first strategy has two primary objectives:

1) help assure technical correctness, accuracy, and completeness, and

2) eliminate unnecessary complexity, poor organization, and ineffective documentation in the guidelines.

A procedures related classification of errors has been developed during this project and is shown in Figure 10.5. In the last example developed in Chapter 9, a qualitative profiling instrument that addressed the quality aspects of a structure design procedure was proposed. The attributes of this instrument are summarized in Table 10.4.

It should be one of the functions of the first strategy to enhance the quality of the design guideline as much as is reasonable or warranted. The objective is to help minimize design team errors that are caused by errors due to procedures and processes.

In the first Strategy, the qualitative and quantitative methods developed and illustrated during this project should be implemented into specific parts of the LRFD design guideline to identify the specific parts of the guideline that should receive additional attention. This project has resulted in definition of technology that can be used to help improve the quality of the LRFD guidelines. It should be used.

Strategy 2

The second strategy is to embody QA / QC directly and explicitly into the design guideline. In this case, requirements for assuring adequate quality in the designers are spelled out. Checking procedures are defined that are appropriate for the particular ship structure. Explicit provisions are made for the correction of errors committed during the design process.

The qualitative and quantitative methods developed and illustrated during this project should be implemented into specific parts of the LRFD design guideline to identify the specific parts of the guideline that should subject to QA / QC.

Design procedure QA / QC approaches have been discussed in Chapter 7. The essence of the approaches is summarized in Table 10.3. Of particular importance is the guiding principle of checking "high likelihood of error parts" such as loading analyses, and checking "high consequences of error parts" of the design process such as design documentation.

Also of importance is the need to be independent from the circumstances which lead to the generation of the design. This refers directly to the need for independent, third-party verification to disclose embedded errors and flaws in the design. Research and experience both indicate that given that it is done properly, third party verification is the most effective way to detect potential problems in the structure design process.

In the author's experience as a marine structure designer, as a manager of marine engineering design groups, and as a third party verification agent for a wide variety of marine structures (spanning 40 years), it unusual that any serious checking of the structure design is performed. Checking, QA / QC, and verification of the structure design are more what we should do than what we actually do. This is satisfactory when the designs are evolutionary, the design processes well established and proven, the system is highly forgiving, and experienced engineers are at the helm of the design team. This is not satisfactory when the designs are revolutionary, the procedures are not well

established and proven, the system is not forgiving, and experienced engineers are not at the helm of the design team.

Recently, the author has been involved in investigation of the failure of a major offshore platform. The failure occurred during installation of the platform. The roots of the failure were imbedded in a design flaw; a failure to address a critical phase of the platform installation.

The design process involved extensive QA / QC. Throughout the design phase, there was a concerted effort to involve the constructor with the design team. Weekly meetings were held to identify, discuss, and resolve design and construction problems. There was extensive QA / QC documentation. A leading Classification Society performed "independent" design and construction reviews. Throughout the project, technical representatives from several major oil companies also performed design reviews.

Given the extensive QA / QC measures, the question was: how and why did the critical flaw slip through? It is noteworthy that one engineer apparently did identify the potential critical flaw. To this engineer, "it didn't look right". But, the groups' consideration of the potential critical flaw did not confirm that it was any problem. As one engineer involved in the checking put it: "no one could prove that there was a problem". The group was concerned with other potentially more serious problems, and in the end, the concern for the potential problem was dismissed. In addition, toward the conclusion of the design phase, there were substantial pressures to complete the work on time and on budget. Worry about "unimportant" details had to be surrendered.

Could the critical flaw have been detected before the accident? Examination of the evidence by a group of experts clearly identified that the flaw could have been detected. Close study of the of the evidence indicates that the flaw was missed for three primary reasons. The first reason was diversion of attention to "more important problems." A high consequence factor was not addressed. The second reason was that the verification and checking that was performed was not "independent" from the circumstances that resulted in the critical flaw. The attention of the checking efforts was diverted just as the attention of the design and construction efforts were diverted. The third reason was the pressure to complete the work on time and on budget. Sufficient resources could not be made available to solve the problem even though the potential problem could be relatively easily and cheaply solved.

This experience points out the importance of truly independent, experienced, and thorough verification of potentially high consequence design "details" (Table 10.3). The cost of such verification and the preventative measures would have been much cheaper than the costs of solving the construction problem. Every dollar invested in prevention could have saved approximately 2,000 dollars in cure. Not many business investments have such an attractive cost - benefit ratio.

Note in Table 10.4 the design procedure quality attributes of intuitive, first principles, and empirical verifications in a design procedure. Intuitive verifications are derived from the designer "feel" cited earlier. Such feel is based on adequate experience with the design procedures and analyses. This feel is responsible for a majority of quality problems that are detected and corrected (design near misses).

First principles verification is needed so that complexity is not allowed to over-shadow realism. This means first that design engineers need to be well trained in these first principles, and second, that the design process must allow and encourage their use in verifying the results from the process.

Experience has indicated that results from simplified methods that employ first principles can play an important role in identifying problems in results from complex methods. Yet, there is often little "respect" given to such methods by engineers. They feel that complex methods are more reliable and give more realistic results. Simplified methods can not be expected to develop the details developed by complex methods. However, sophistication in analytical design methods does not assure either reliability or realism in results. There is an important need to further develop simplified design methods that can be used to help verify the fundamental results from complex design analyses.

Empirical or experimental verification is needed because of the inherent inadequacies and limitations of most engineering analytical procedures when applied to design of ship structures. This is particularly true when it comes to loading analyses, but it also applies to most structure analyses. The question is the extent of experimental verification that is required. This becomes a problem in trading off the costs involved in providing the verification versus the costs involved when insufficient quality is obtained due to the lack of the verification.

The LRFD design guideline should encourage the use of all three verification procedures as warranted. Particular emphasis should be given to the requirements for independent, experienced, and thorough verification of "new designs" of ship structures.

Strategy 3

The third strategy that should be incorporated directly into the design guidelines and their development regards design of the structure to be tolerant or forgiving of human errors. These human errors can and probably will occur in design, construction and operation of a ship structure; even one that has been designed by the most advanced technology available today.

It is rare to find explicit structure design guidelines that address the need for obtaining human error tolerance in the life-cycle of any type of structure. Some have begun to appear, but more work is needed to develop such

guidelines. This is one of the most important areas for marine structures research.

The results of the MSIP project [Bea, 1993] indicated that there were four general approaches that should be considered in developing human error tolerant structure design guidelines. These were design for:

1) damage or defect tolerance (robustness),
2) constructabilty,
3) inspectability, and
4) maintainability and repairability.

The first approach is focused on providing fault tolerance in the ship structure system. The last three approaches are focused on providing fault avoidance, detection, and removal in the ship design process.

Structure robustness can be achieved with a combination of redundancy, ductility, and excess capacity in the structure system. Robustness implies much more than redundancy (degree of indeterminacy) [Das, Garside, 1991]. Fail-safe design is one aspect of this approach [Bea, 1992].

Robustness needs to be placed in those areas of the ship structure that have high probabilities of damage or defects and high consequences associated with such damage or defects. Such an approach has been used recently in design of several major offshore platforms [Bea, 1994c]. The approach had major effects on the configuration of the structures.

Design for constructability is focused on configuration and proportioning the structure to promote / facilitate high quality materials, cutting and forming, and assembly. Design for inspectability is focused on the same structure design activities, but this time the objective is to maximize the inspectability of the ship structure during its operation. Design for maintainabilty and reparability is meant to direct the structure design engineers attention to the long-term life-cycle phase of the ship structure. Corrosion management and buckling and fracture repairs are key issues.

All of these design approaches are intended to minimize the incidence of and effects of human errors that can occur in design, construction, and operation of a ship structure.

Explicit design guidelines should be developed that will adequately address the four major quality attributes of the ship structure including serviceability, safety, durability, and compatibility. In addition, structure design guidelines need to be developed that will address the constraints and issues associated with potential damage and defects in the structure, its construction, its inspection, and its maintenance and repair.

Summary

This chapter has addressed the question of whether or not consideration of HOE should be integrated into development of the new LRFD ship structure design procedure being developed under the auspices of the SSC. The answer is yes, consideration of HOE should be integrated into this procedure.

This chapter has addressed three ways in which such considerations might be developed. These include organizational measures, design team (individuals) measures, and design procedure measures.

Perhaps of primary importance to the future SSC efforts are the design procedure measures. Three strategies have been suggested that involve:

- QA / QC of the design procedures (fault avoidance),

- QA / QC required as an integral part of the design procedures (fault detection and removal), and

- LRFD design procedures intended to minimize the occurrence of and effects of HOE (fault tolerance).

In a review of the processes used by the U. S. Coast Guard in certifying the safety of marine vessels and structures, a committee of the Marine Board of the National Academy of Engineering made the following recommendations [Committee on Assuring the Safety of Innovative Marine Structures, 1991]:

- Personnel and staffing - broad based mix of technical expertise and practical experience in a professional working environment.

- Polices and Practices on the Use of Third Parties - use outside expertise and assistance as needed including collaboration with ABS.

- Development of Technical Criteria - procedures for establishing technical criteria for certification, development of a searchable and retrievable data base of applications, reviews, and decisions.

- Lessons to be Learned from Other Agencies - examine the FAA and NRC data retrieval and feedback systems for applicability, consider the use of expert panels in the review process.

- Emerging Technologies - keep abreast of an understand the implications and applications of new and emerging technologies to the certification process, risk and reliability engineering is one example.

These recommendations are embodied in the findings from this project and the associated previous MSIP project [Bea, 1993].

Chapter 11

FUTURE DEVELOPMENTS: STRUCTURE DESIGN GUIDELINES

Introduction

This chapter identifies high priority developments that are suggested as future SSC sponsored efforts. These developments are essential if the background developed during this project is to be applied in efforts to improve the quality of the design of ship structures.

The following parts of this chapter will address future developments in ship structure design in two general categories:

- LRFD design guidelines, and
- HOE evaluation qualitative and quantitative methods.

LRFD Design Guidelines

This project explored the implications of HOE as they related to development of a probability based LRFD guideline for ship structures. The study concluded that the improved management of HOE in the design guidelines should be developed using two approaches:

1) Quality Assurance and Quality Control (QA / QC) in the development of the design guideline and incorporated explicitly into the guideline.

2) Provision of design guidelines to help assure defect and damage tolerance in the structure and to promote constructability, and IMR.

These two approaches are intended to help prevent design errors, improve the detection and correction of errors, and develop a structure that will have sufficient tolerance of errors.

This conclusion suggests four SSC sponsored efforts that are intended to recognize and help better manage HOE in an LRFD guideline for ship structures:

1) QA / QC of the design guideline during its development,

2) Development of QA / QC provisions that would be incorporated into the design guideline,

3) Development of design guidelines to assure adequate robustness in the ship structure, and

4) Development of design guidelines to assure adequate constructability, inspectability, maintainability, and repairability in the ship structure.

The majority of the required engineering and QA / QC technology exists to help accomplish each of these efforts. The SSC has sponsored much of the research and development that has resulted in this technology.

Background needs to be assembled from the marine and non-marine fields, work performed to "fill in the blanks" in the technology, and the results focused in development of practical ship structure design guidelines.

These developments should be thoroughly tested in demonstration efforts that will help assure that the provisions, guidelines, and procedures are practical.

Qualitative and Quantitative Methods

The results of this project indicate that there is a wealth of technology available to allow engineers to explicitly address HOE in the design, construction, and operation of ships.

This technology needs to be further developed and applied if the profession and industry are to realize significant improvements in the quality of ship structures. The results from this project have suggested two primary lines for this development:

- Conduct of symposia, workshops, and meetings on human and organization factors and their roles in the quality of ship structures,

- Further development and testing of qualitative and quantitative instruments methods to address design of specific ship structures in the context of LRFD procedures.

Technology Transfer

A program of symposia, workshops, and meetings sponsored by the Ship Structure Committee would further understanding of human factors and their roles in the quality of ship structures. Technology and experience transfer is a primary objective of this activity. The program needs to be international in scope.

This activity would facilitate the education processes that must be undertaken if developments such as are represented by this project are to be improved, detailed, tested, and applied. These symposia, workshops, and meetings should involve protagonists and antagonists; researchers and practitioners; and those from outside the engineering disciplines that have expertise in human factors related technologies.

Development of HOE Evaluation Procedures

This project has resulted in development and illustration of application of qualitative and quantitative methods to enable engineers to address HOE considerations in the design and construction of ship structures. These methods need to be further developed as they can be applied to development of LRFD guidelines for ship structures.

Four specific SSC sponsored efforts are suggested to address HOE considerations in design and construction of ship structures:

1) *Study of how best to integrate considerations of the four quality attributes into a ship structure design guideline.*

2) *Identification of the critical parts of the ship structure design processes, and evaluation of how QA / QC procedures might best be deployed in the processes.*

3) *Study of where and how robustness (defect tolerance) and fail-safe design should be integrated into the ship structure and the design guidelines.*

4) *Continued development of the qualitative, quantitative, and mixed HOE evaluation approaches defined during this project are needed as they would be applied to specific LRFD design guideline and design processes. The mixed, Safety Indexing Method (Appendix C), approach requires development and testing as applied to the LRFD design guideline and design process. Development, testing, and practical demonstrations of computer software to facilitate performing the quantitative and mixed HOE alternatives evaluations is needed.*

Summary

Future SSC sponsored efforts have been defined to apply the results from this project in improving the quality of what is integrated into a ship structure design guideline. These efforts address the following HOE considerations:

- technical aspects of ship structure design (e. g. defect and damage tolerance),
- development of ship structure design guidelines (e. g. QA / QC in the design process),
- development of qualitative and quantitative methods to address HOE management alternatives in ship structure design, and
- education in how human, organization, procedure, and hardware factors can affect the quality of ship structures.

Chapter 12

SUMMARY & CONCLUSIONS

Summary

Quality is freedom from unanticipated defects. Quality is fitness for purpose. Quality is meeting the requirements of those that own, operate, design, construct, and regulate ship structures. These requirements include those of serviceability, safety, compatibility, and durability.

There are three primary aspects that should be addressed in achieving quality in ship structures: designers, constructors, and operators of the structure (humans), the groups that are responsible for the management of the systems (organizations), and the physical elements (system including structure, hardware, and software). A thorough understanding of ship structure "systems" indicates that there literally are no separate parts. There are only relationships and interactions. This understanding is at substantial variance with the historical separation and compartmentation of ship structure design, construction, and operation.

High consequence compromises in quality of ship structures result from a multiplicity or compounding sequence of break-downs in the human, organization, and system; often there are "precursors" or early warning indications of the break-downs that are not recognized or ignored.

The physical components of "systems" are generally the easiest of the three components to address; design for human tolerances and capabilities (ergonomics), provision of redundancy and damage / defect tolerance, and effective early warning systems that provide adequate time and alerts so that systems can be brought under control are examples of potential measures. Error inducing systems are characterized by complexity, close coupling, latent flaws, small tolerances, severe demands, and false alarms.

Humans are more complex in that error states can be developed by a very wide series of individual characteristics and "states" including fatigue, negligence, ignorance, greed, folly, wishful thinking, mischief, laziness, excessive use of drugs, bad judgment, carelessness, physical limitations, boredom, and inadequate training. External (to the system) and internal (in the

system) environmental factors such as adverse weather, darkness, smoke, heat provide additional influences.

Selection (determination of abilities to handle the job), training (particularly crisis management), licensing, discipline, verification and checking, and job design provide avenues to improve the performance of front-line operators. The formation of motivated and cohesive design and construction "teams" can do much to improve the quality of ship structures.

While the human and system aspects are very important, the organization aspects frequently have over-riding influences. Corporate "cultures" focused on production at the expense of quality, ineffective and stifled communications, ineffective commitment and resources provided to achieve quality, excessive time and profit pressures, conflicting corporate objectives, and counter-quality and integrity incentives are often present in "low reliability" organizations. Generally, these aspects are the most difficult to address. Experience indicates that high reliability organizations tend to improve, while low reliability organizations do not improve rapidly, if at all.

The most important part of the HOE evaluation process is qualitative; a realistic and detailed understanding of the human, organization, and system aspects and potential interactions must underlie the entire process. Quantitative aspects provide an important framework in which to evaluate the potential effectiveness of proposed "fixes" and to examine the detailed interactions of human, organization, and system components.

The results from this project indicate that we should change our thinking away from a concept of ship structure systems as elements, components, and separate structures and understand them as integrated systems that intimately involve individual and collective (organizations) human beings. We need to understand these systems as organisms, living systems, that can harbor latent pathogens [Reason, 1991].

There is no ship structure design and construction quality database that can be relied upon to give accurate quantitative indications of the frequencies of contributors to unacceptable quality; in the case of specific accident scenarios, existing databases frequently give misleading indications of causes and consequences. Complex interactions are frequently not determined or lost in the reporting. Study of past high consequence accidents can provide important insights into the complex interactions of humans, organizations, and systems and can provide the basis for development of generic "templates" for evaluation of other similar systems. Study of "near misses" can show how potentially catastrophic sequences of actions and events can be interrupted and brought under control. There is no generally available database or archiving system for "near miss" information. This state of affairs needs to be improved; such databases need to be developed and there are existing models for such developments.

An adequate and understandable, but complex, quantitative analysis system exists to assist evaluations of HOE. PRA has proven to be able to show the complex interactions and influences and efficiently produce quantitative indices that can indicate the effectiveness of alternative HOE "fixes." Because of the lack of accurate and definitive objective data to serve as input to such quantitative models, structured "index" models have been developed to allow encoding subjective judgment into the evaluation of probabilities. More work is needed to develop both the qualitative and quantitative methods so that they can be applied to improve the quality of ship structures.

The primary objective of QA / QC assessments and HOE evaluations should not be to produce numbers. The primary objective of the assessments should be to provide a disciplined and structured framework that is able to produce insights and information that can lead to improvements in QA / QC activities to achieve desirable quality in ship structures. Prediction is not the objective of this effort. Improvement in quality is the objective. The analyses should be performed to provide the insights that can help define how best to develop acceptable and desirable quality in ship structures.

Some of the parameters and variances, and in many cases, the very important ones can not be quantified with a high degree of reliability. In most cases, these are the parameters and variances that address the inter-relationships of individuals and organizations. Perhaps the most important figures that one needs for quality management and quality engineering are unknown or unknowable.

To take any action with a ship structure design, construction, or operation system without an intimate and thorough knowledge of that system is "tampering." Deep knowledge of a system includes a detailed understanding of the system, an understanding of qualitative and quantitative evaluations, a knowledge of psychology (individuals, organizations), and an understanding of the limitations of our abilities to describe and analyze complex systems. Without a deep knowledge of the system, one can be seriously mislead.

The primary responsibilities for determining and achieving desirable and acceptable quality in ship structures rests with the owner and operator of the ship. The owner and operations segments play a pivotal role in the organization for quality. The owner and operator are substantially responsible for the quality of any ship. They are responsible for establishing the system requirements and objectives and communicating them to the other organizations. The owner / operator is responsible for consideration of the relationships of cost and performance and function.

The regulatory authorities should be responsible and accountable for definition and verification of compliance with the goals and policies of acceptable quality in ship structures.

Classification authorities should be responsible and accountable for development of classification rules that will guide and verify design, construction, and operation of acceptable quality ship structures that meet regulatory and owner requirements. Surveying during the construction and operational phases is an essential part of this responsibility. Independent third-party verification of designs is another essential component.

The manufacturers of ship structures should be responsible for designing and producing marine structures that will have appropriate and desirable levels of quality.

Specific approaches and examples have been developed during this project to illustrate how human factors might be integrated into the ship structure design process. This work needs to be continued and extended into construction and operation of ship structures if we are to realize dramatic improvements in the quality of these structures.

Conclusions

The author contends that:

"most engineers are very uncomfortable with two things: uncertainty, and people."

The challenges of design, construction, and operation of ship structures involves both. Neither can or should be avoided.

Engineers have much to learn about how to improve their role and activities in helping develop engineered systems that will have desirable and adequate quality. A vast field of human factors related technology has developed. The analytical thinking and processes of engineering needs to absorb the technologies of human psychology, management, and cognitive psychology.

The analytical thinking and processes of engineering need to shift from the objective of prediction to the objective of evaluation, assessment, and improvement of the processes that are used to design, construct, and operate ship structures.

If their work is to be meaningful, engineers must learn as much about people as they presently know about the physical and mechanical aspects of the elements that comprise and affect engineered systems. Recognition of and education in human factors are two of the primary obstacles to integration of human factors into engineering.

The historic development of LRFD guidelines has had as one of its foundation probability methods that attempt to address some of the

uncertainties. In almost all cases, this historic development has fallen short of explicitly addressing one of the primary sources of uncertainty and hazards to quality: people.

Many of the experienced engineers that have objected to probability based LRFD developments have objected to this development primarily for this reason. They sense that something important is missing, and it is. But, the same thing is also missing from the more traditional methods. And, in the main, it is for this reason that we are now recognizing the reasons for the majority of compromises in the quality of both marine and non-marine structures are firmly rooted in HOE.

This project has attempted to start development of a bridge between where we are and where we can be in recognizing human factors in design of ship structures. HOE recognition can and should be integrated into our future developments to improve the quality of ship structures. The basic tools exist. They need to be further developed, tested, and wisely used.

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Appendix A

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Appendix B

DEFINITION OF ACRONYMS

ABS	- American Bureau of Shipping
ACI	- American Concrete Institute
ASCE	- American Society of Civil Engineers
CAIP	- Critical Area Inspection Plan
CSD	- Critical Structural Details
DOC	- Document of Compliance
DPL	- Decision Programming Language
EDA	- Events, Decisions, and Actions
ENR	- Engineering News Record
ETA	- Event Tree Analyses
FAA	- Federal Aviation Administration
FEA	- Finite Element Analyses
FLAIM	- Fire and Life safety Assessment Indexing Method
FMEA	- Failure Mode and Effects Analyses
FTA	- Fault Tree Analyses
GRT	- Gross Registered Tonnage
HazOps	- Hazard and Operability analyses
HESIM	- Human Error Safety Index Method
HOE	- Human and Organization Errors
HRA	- Human Reliability Analysis
HRO	- High Reliability Organization
HRO	- High Reliability Organizations
HTS	- High Tensile Steel
IABSE	- International Association of Bridge and Structure Engineers
IACS	- International Association of Classification Societies
ICAM	- Integrated Computer Aided Manufacturing
ICS	- International Chamber of Shipping

IDA	- Influence Diagram Analyses
InDia	- Influence Diagramming (computer program)
IDEF	- ICAM Definition language
IMO	- International Maritime Organization
IMR	- Inspection, Maintenance, and Repair
ISM	- International Safety Management
ISO	- International Standards Organization
ISSC	- International Ship and offshore Structures Congress
LER	- Licensee Event Report
LRFD	- Load and Resistance Factor Design
MSIP	- Marine Structural Integrity Programs
NRC	- Nuclear Regulatory Commission
NC	- Norwegian Contractors
OPA	- Oil Pollution Act
POD	- Probability of Detection
PRA	- Probabilistic Risk Analyses
QA	- Quality Assurance
QC	- Quality Control
QMS	- Quality Management System
QRA	- Quantified Risk Analyses
SIM	- Safety Index Method
SMC	- Safety Management Certificate
SMS	- Safety Management System
SOLAS	- Safety of Life at Sea (Convention)
SSC	- Ship Structure Committee
SSIIS	- Ship Structural Integrity Information System
THERP	- Technique for Human Error Rate Prediction
TQC	- Total Quality Construction
TQE	- Total Quality Engineering
TQM	- Total Quality Management
TQO	- Total Quality Operations
ULCC	- Ultra Large Crude Carrier
USCG	- United States Coast Guard
VLCC	- Very Large Crude Carrier
VTS	- Vessel Traffic System
WSD	- Working Stress Design

APPENDIX C

HESIM & FLAIM SAFETY INDEXING METHODS

Safety Indexing Methods

Safety Indexing Methods (SIM) have been used successfully in a variety of marine and non-marine applications as a means of identifying potential quality / reliability problems and then identifying means to improve the reliability and quality characteristics of the systems. SIM represent a logical and disciplined way to bridge the gap between the lack of definitive information on HOE and the need to improve the quality of engineered systems.

The core of these methods is formed by professional judgment based on qualified experience and training, historical records, and in some cases, hazard evaluation techniques such as Hazard and Operability Studies (HazOps) and Event Tree Analyses (ETA). This core is used to identify, select, and define key variables that are risk contributors and risk mitigators. These variables are then combined by using various algorithms to yield risk indices indicative of the state of the system. An overall risk index can be generated to compare different facilities and options to improve their quality characteristics. This risk index can be calibrated to quantitative quality - reliability - probability of failure evaluations. Cost-benefit evaluations can be based on the results from Safety Indexing Methods.

Given accident and near-miss investigations databanks that are designed to supply information required by the SIM and the long-term implementation of these reliability databanks, the subjectivity involved in the methods can be gradually replaced by objective information.

During the past five years, two such methods have been developed from research performed under the auspices of the Marine Technology Development Group at the University of California at Berkeley. One system developed during the Doctoral research performed by Dr. W. H. Moore was developed for the evaluation of HOE in the operations of marine systems [Moore, Bea, 1993]. This system is identified as *HESIM - Human Error Safety Indexing Method.*

The second method was developed in the Doctoral research performed by Dr. W. E. Gale Jr. for the evaluation of HOE in fires and explosions on offshore platforms [Gale, Bea, Williamson, 1993; Gale, et al, 1994]. This system is identified as *FLAIM (Fire and Life Safety Assessment Indexing Method.*

Because of their potential future applications to evaluations of HOE in the design and construction of ship structures, these two methods are summarized in this appendix.

HESIM

HESIM was developed to allow the encoding of judgment regarding the occurrence of HOE in *operations* of marine systems in a probabilistic framework. HESIM integrates error inducing parameters (error solicitors) that can lead to an operating accident event. The error solicitors are organizational, human, task, system, and environmental factors.

HESIM incorporates error factors from four categories of primary contributors: (1) organizational, (2) human, (3) system, and (4) the operating environment. Table C.1 defines the contributing factors in each of these categories.

Table C.1 - Categorization of contributing factors to HESIM

ORGANIZATION	HUMAN	SYSTEM	OPERATING ENVIRONMENT
Top-level Management	Stress	Complexity	External
Middle - Front-line Management	Routineness		Internal
Regulatory			

HESIM is a consolidation of heuristic approaches and the development of an accident database. HESIM provides the framework for development of an accident and near-miss database [Moore, Bea, 1993]. As detailed accident data becomes more available for particular accident classes, the risk indices are refined to correlate with the casualty statistics. The conditional human error index is used as a quantitative measurement for IDA. It is not a probabilistic measure, but a means by which to systematically quantify human errors. These measures form a basis from which future error index refinements, modifications, and verifications are made until sufficient data is available to use probabilistic measurements.

Equation C.1 is the generalized equation integrating contributing HOE factors.

$$SI_{HE_i,OE_j,HF,Syst,Env,EDA_q} = k_{ij} SI_{HE_i|OE_j,HF,Syst,Env,EDA_q} * SI_{OE_j,EDA_q} \\ * SI_{HF,EDA_q} * SI_{Syst,EDA_q} * SI_{Env,EDA_q} \tag{C.1}$$

Each safety index SI, lies between 0 and 1 and k_{ij} is a factoring constant for human error i and organizational error j: $0 \le SI \le 1$.

The overall human error index is the quantitative measurement of human and organizational errors, human factor, system, and environmental factors occurring for a specified event, decision, or action. The *overall human error safety index* ($SI_{HEi,OEj,HF,Env,Syst,EDAq}$) is the product of five safety indices:

(1)*human error safety index* ($SI_{HEi|OEj,HF,Env,Syst,EDAq}$) ,
(2) *organizational error index* ($SI_{OEj,EDAq}$),
3) *human factor index* ($SI_{HF,EDAq}$),
(4) *system index* ($SI_{Syst,EDAq}$), and
(5) *environmental index* ($SI_{Env,EDAq}$).

As shown in Equation C.2, the measure of the overall human error safety index is a weighted frequency of the factors for a specified class of accidents (e.g. tanker collisions or grounding, offshore production-maintenance explosions, and fires).

$$\left\{SI_{HE_i,OE_j,EDA_q,HF,Syst,Env}\right\}_k = 1 - \left\{f_{HE_i,OE_j,EDA_q,HF,Syst,Env}\right\}_k \\ = 1 - \frac{1}{m}\sum_m \left\{\xi_{HE_i,OE_j,EDA_q,HF,Syst,Env}\right\}_{km} \tag{C.2}$$

$$\xi_{\substack{HE_i,MOE_j,EDA_q,TLM \\ HF,Syst,Env}} = \begin{cases} 0 \text{ no relation} \\ \frac{1}{3} \text{ "low" certainty of relation between } HE_i \text{ and } MOE_j \\ \frac{1}{2} \text{ "moderate" certainty of relation between } HE_i \text{ and } MOE_j \\ 1 \text{ "high" certainty of relation between } HE_i \text{ and } MOE_j \end{cases}$$

where k is the consequence level of the casualty, and m is the total number of operations per measurement of time for that consequence level.

Weighted values are assigned that depend upon the certainty of that factor being a contributor to a casualty-near miss sequence. The error frequency is determined by averaging across the weighted frequencies of joint occurrences between the five categories under all external operating

conditions, human factors, and system complexity. For each casualty-near miss, the associated human, organizational, human factor, system, and environmental contributor is defined. The certainty values are placed in the proper location for the joint occurrences as shown in Table C.2.

The human error index is the quantitative measurement of human error conditional upon a set of organizational errors, human factors, system and environmental factors for a specified sequence of Events, Decisions and Actions (EDA). By solving for the human error index of Equation C.1 to arrive at Equation C.3, one is able to use these values as quantitative measurements of human errors under varying organizational, human factor, system, and environmental conditions. Again it should be noted that the human error index generated by this technique is not a probability, but an index value conditional upon any number of error solicitors. These are the conditional safety indices that are used in the IDA.

$$\left\{SI_{HE_i|OE_j,HF,Syst,Environ,EDA_q}\right\}_k = \frac{\left\{SI_{HE_i,OE_j,HF,Syst,Environ,EDA_q}\right\}_k}{k_{ij} * SI_{OE_i,EDA_q} * SI_{HF,EDA_q} * SI_{Syst,EDA_q} * SI_{Env,EDA_q}} \tag{C.3}$$

The next step is to provide a methodology for measuring the safety indices in the denominator of Equation C.3. The *organizational error safety index* ($SI_{OEj,EDAq}$) shown in Equation C.4 is a measure of the impact of top-level management upon mid-level management and operator level management errors (MOE) effects upon human errors (HE) at the operator level. A matrix representation of Equation C.4 is shown in Table C.3. The index is assumed to be relatively static over short periods of time for an operation [Reason, 1992].

$$SI_{OE_j,EDA_q} = SI_{MOE_j|TLM} * SI_{MOE_j,EDA_q} \tag{C.4}$$

As shown in Equation C.7, the organizational error index is differentiated into two categories. First, the *top-level management index* ($SI_{MOEj\,|\,TLM}$) measures the level of Top-Level Management (TLM) commitment to safety and resource allocation for safety measures. The TLM commitment to safety and resources has varying degrees of impact upon MOEs.

In Equation C.5, $SI_{MOEj\,|\,TLM}$ is the safety index of TLM's impact upon MOE_j Varying degrees of impact are measured by weighing the impact of five TLM factors:

(1) *overall commitment to safety* (Q_1),
(2) *commitment to long term safety goals* (Q_2),
(3) *cognizance of problems* (Q_3),
(4) *competence to correct the problem* (Q_4), and
(5) *sufficient resources to correct problems* (Q_5)

such that,

$$\begin{aligned}
SI_{MOE_1|TLM} &= \max\left\{\phi_{11}Q_1 + \phi_{21}Q_2 + \phi_{31}Q_3 + \phi_{41}Q_4 + \phi_{51}Q_5, \left(SI_{MOE_1|TLM}\right)_o\right\} \\
SI_{MOE_2|TLM} &= \max\left\{\phi_{12}Q_1 + \phi_{22}Q_2 + \phi_{32}Q_3 + \phi_{42}Q_4 + \phi_{52}Q_5, \left(SI_{MOE_2|TLM}\right)_o\right\} \\
&\vdots \\
SI_{MOE_j|TLM} &= \max\left\{\phi_{1j}Q_1 + \phi_{2j}Q_2 + \phi_{3j}Q_3 + \phi_{4j}Q_4 + \phi_{5j}Q_5, \left(SI_{MOE_j|TLM}\right)_o\right\} \\
&\vdots \\
SI_{MOE_9|TLM} &= \max\left\{\phi_{19}Q_1 + \phi_{29}Q_2 + \phi_{39}Q_3 + \phi_{49}Q_4 + \phi_{59}Q_5, \left(SI_{MOE_9|TLM}\right)_o\right\} \\
SI_{MOE_{10}|TLM} &= 1
\end{aligned} \tag{C.5}$$

where,

$$Q_c = \begin{cases} 1 & \text{if "high" or "sufficient"} \\ -1 & \text{if "low" or "insufficient"} \end{cases}$$

$$\sum_a \phi_{aj} = 1 \qquad \forall j$$

If the TLM factor is "high" or "sufficient", it adds to the safety index, however if "low" or "insufficient", it reduces that safety index. The weights can be thought of as the percent of impact upon MOEs by TLM factors. Since MOE_{10} represents no organizational errors, there is no impact of TLM on MOE_{10} thus the safety index is unchanged.

Table C.2 - Documentation format of human errors and associated organizational errors for accident class n, consequence n_k, EDA_q, human factors, system factors, and environmental factors

Human Errors (HE_i)	know/ training/ exper (MOE_1)	maint-enance (MOE_2)	violation (MOE_3)	morale/ incentive (MOE_4)	job design (MOE_5)	regul/ policing (MOE_6)	operating policy (MOE_7)	comm/ info (MOE_8)	manning (MOE_9)	none (MOE_{10})
hum/syst interface (HE_1)	ξ_{11kq}	ξ_{12kq}	ξ_{13kq}	ξ_{14kq}	ξ_{15kq}	ξ_{16kq}	ξ_{17kq}	ξ_{18kq}	ξ_{19kq}	$\xi_{1,10kq}$
know/train/ exper (HE_2)	ξ_{21kq}	ξ_{22kq}	ξ_{23kq}	ξ_{24kq}	ξ_{25kq}	ξ_{26kq}	ξ_{27kq}	ξ_{28kq}	ξ_{29kq}	$\xi_{2,10kq}$
mntl/phys lapse (HE_3)	ξ_{31kq}	ξ_{32kq}	ξ_{33kq}	ξ_{34kq}	ξ_{35kq}	ξ_{36kq}	ξ_{37kq}	ξ_{38kq}	ξ_{39kq}	$\xi_{3,10kq}$
violations (HE_4)	ξ_{41kq}	ξ_{42kq}	ξ_{43kq}	ξ_{44kq}	ξ_{45kq}	ξ_{46kq}	ξ_{47kq}	ξ_{48kq}	ξ_{49kq}	$\xi_{4,10kq}$
job design (HE_5)	ξ_{51kq}	ξ_{52kq}	ξ_{53kq}	ξ_{54kq}	ξ_{55kq}	ξ_{56kq}	ξ_{57kq}	ξ_{58kq}	ξ_{59kq}	$\xi_{5,10kq}$
comm/inξo (HE_6)	ξ_{61kq}	ξ_{62kq}	ξ_{63kq}	ξ_{64kq}	ξ_{65kq}	ξ_{66kq}	ξ_{67kq}	ξ_{68kq}	ξ_{69kq}	$\xi_{6,10kq}$

where,

$$\xi_{ijkq} = \left\{ \xi_{HE_i, OE_j EDA_q, HF, Syst, Env} \right\}_k$$

Table C.3 - Safety indices of human associated organizational errors for accident class n with consequence v_k and event, decision, or action q

Human Errors (HE_i)	know/ training/ exper (MOE_1)	maint- enance (MOE_2)	violation (MOE_3)	morale/ incentive (MOE_4)	job design (MOE_5)	regul/ policing (MOE_6)	operating policy (MOE_7)	comm/ info (MOE_8)	manning (MOE_9)	none (MOE_{10})	*Marginal Safety Index of HE_i* (SI_{HE_i})
Top level management (TLM)	x $SI_{MOE_1/TLM}$	x $SI_{MOE_2/TLM}$	x $SI_{MOE_3/TLM}$	x $SI_{MOE_4/TLM}$	x $SI_{MOE_5/TLM}$	x $SI_{MOE_6/TLM}$	x $SI_{MOE_7/TLM}$	x $SI_{MOE_8/TLM}$	x $SI_{MOE_9/TLM}$	x $SI_{MOE_{10}/TLM}$	
hum/syst interface (HE_1)	$SI_{HE_1OE_1}$	$SI_{HE_1OE_2}$	$SI_{HE_1OE_3}$	$SI_{HE_1OE_4}$	$SI_{HE_1OE_5}$	$SI_{HE_1OE_6}$	$SI_{HE_1OE_7}$	$SI_{HE_1OE_8}$	$SI_{HE_1OE_9}$	$SI_{HE_1OE_{10}}$	$\{SI_{HE_1}\}_k = \sum_j \{SI_{HE_1OE_j}\}_k$
know/train/ exper (HE_2)	$SI_{HE_2OE_1}$	$SI_{HE_2OE_2}$	$SI_{HE_2OE_3}$	$SI_{HE_2OE_4}$	$SI_{HE_2OE_5}$	$SI_{HE_2OE_6}$	$SI_{HE_2OE_7}$	$SI_{HE_2OE_8}$	$SI_{HE_2OE_9}$	$SI_{HE_2OE_{10}}$	$\{SI_{HE_2}\}_k = \sum_j \{SI_{HE_2OE_j}\}_k$
mntl/phys lapse (HE_3)	$SI_{HE_3OE_1}$	$SI_{HE_3OE_2}$	$SI_{HE_3OE_3}$	$SI_{HE_3OE_4}$	$SI_{HE_3OE_5}$	$SI_{HE_3OE_6}$	$SI_{HE_3OE_7}$	$SI_{HE_3OE_8}$	$SI_{HE_3OE_9}$	$SI_{HE_3OE_{10}}$	$\{SI_{HE_3}\}_k = \sum_j \{SI_{HE_3OE_j}\}_k$
violations (HE_4)	$SI_{HE_4OE_1}$	$SI_{HE_4OE_2}$	$SI_{HE_4OE_3}$	$SI_{HE_4OE_4}$	$SI_{HE_4OE_5}$	$SI_{HE_4OE_6}$	$SI_{HE_4OE_7}$	$SI_{HE_4OE_8}$	$SI_{HE_4OE_9}$	$SI_{HE_4OE_{10}}$	$\{SI_{HE_4}\}_k = \sum_j \{SI_{HE_4OE_j}\}_k$
job design (HE_5)	$SI_{HE_5OE_1}$	$SI_{HE_5OE_2}$	$SI_{HE_5OE_3}$	$SI_{HE_5OE_4}$	$SI_{HE_5OE_5}$	$SI_{HE_5OE_6}$	$SI_{HE_5OE_7}$	$SI_{HE_5OE_8}$	$SI_{HE_5OE_9}$	$SI_{HE_5OE_{10}}$	$\{SI_{HE_5}\}_k = \sum_j \{SI_{HE_5OE_j}\}_k$
comm/info (HE_6)	$SI_{HE_6OE_1}$	$SI_{HE_6OE_2}$	$SI_{HE_6OE_3}$	$SI_{HE_6OE_4}$	$SI_{HE_6OE_5}$	$SI_{HE_6OE_6}$	$SI_{HE_6OE_7}$	$SI_{HE_6OE_8}$	$SI_{HE_6OE_9}$	$SI_{HE_6OE_{10}}$	$\{SI_{HE_6}\}_k = \sum_j \{SI_{HE_6OE_j}\}_k$

Second, the *middle-operator level management safety index* ($SI_{HE_i|MOE,EDA_q}$) is the sum of each organizational error's effect upon a particular human error "i" (HE_i). Each index associates the organizational error's effect upon human errors at the operator level. The minimum value of the impact of top-level management $\left(SI_{MOE_j|TLM}\right)_o$, is provided by the user and should be established such that $\left(SI_{MOE_j|TLM}\right)_o \geq 0$.

To determine the safety index for a particular HE as a result of the organizational errors (OEs), the safety index is determined by providing estimates of the relative effect of "good", "fair", or "poor" organizational error management. Figure C.1 is a graphical display of how routine a safety index is obtained through a linearization technique and described in Equation C.6.

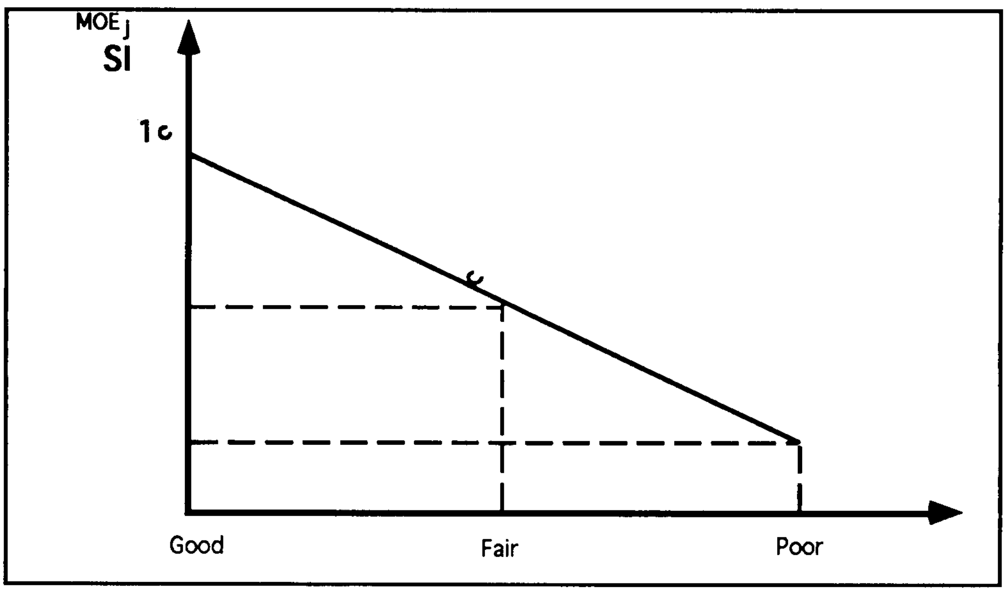

Figure C.1 - Linearized measurement of middle-front line management index

$$SI_{MOE_j,EDA_q} = \begin{cases} 1 & \text{if "high"} \\ 1/2 + 1/2(1/\rho_j) & \text{if "moderate"} \\ 1/\rho_j & \text{if "low"} \end{cases} \qquad (C.6)$$

where r_j is the maximum degree by which MOEj is judged to be increased for EDA_q.

The human factor index described in Equation C.1 is categorized into the product of a *stress index* (SI_{Stress,EDA_q}) and a *routineness index* ($SI_{Routineness,EDA_q}$) as shown in Equation C.7. Stress and routineness are measured to assess the relative effect upon the safety of the system. The user judges the relative effect of "high" stress or routineness. Figure C.2 is a graphical display of how the stress safety index is obtained through a linearization technique and shown in Equation C.8. The index measuring routineness of the EDA_q is linearized and shown in Figure C.3 and the formulation is described in Equation C.9.

$$SI_{\text{Hum factor},EDA_q} = SI_{\text{Stress},EDA_q} * SI_{\text{Routineness},EDA_q} \tag{C.7}$$

$$SI_{\text{StressIEDA}_q} = \begin{cases} 1 & \text{if "low"} \\ 1/2 + 1/2(1/\alpha) & \text{if "moderate"} \\ 1/\alpha & \text{if "high"} \end{cases} \tag{C.8}$$

where a is the maximum degree by which stress is judged to be increased for EDA_q.

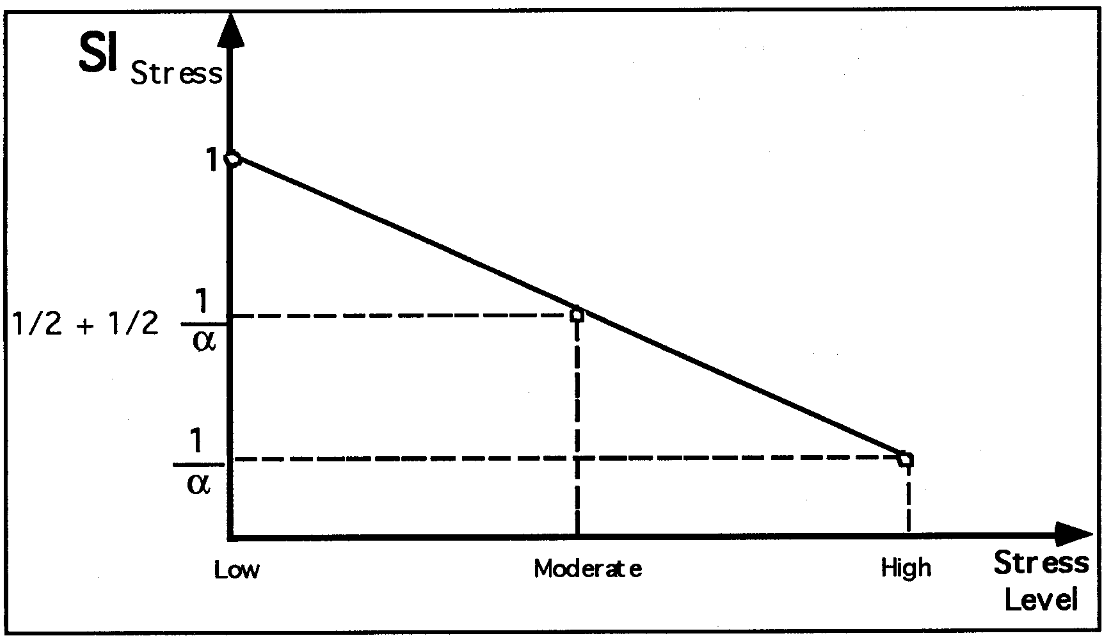

Figure C.2 - Linearized measurement of stress

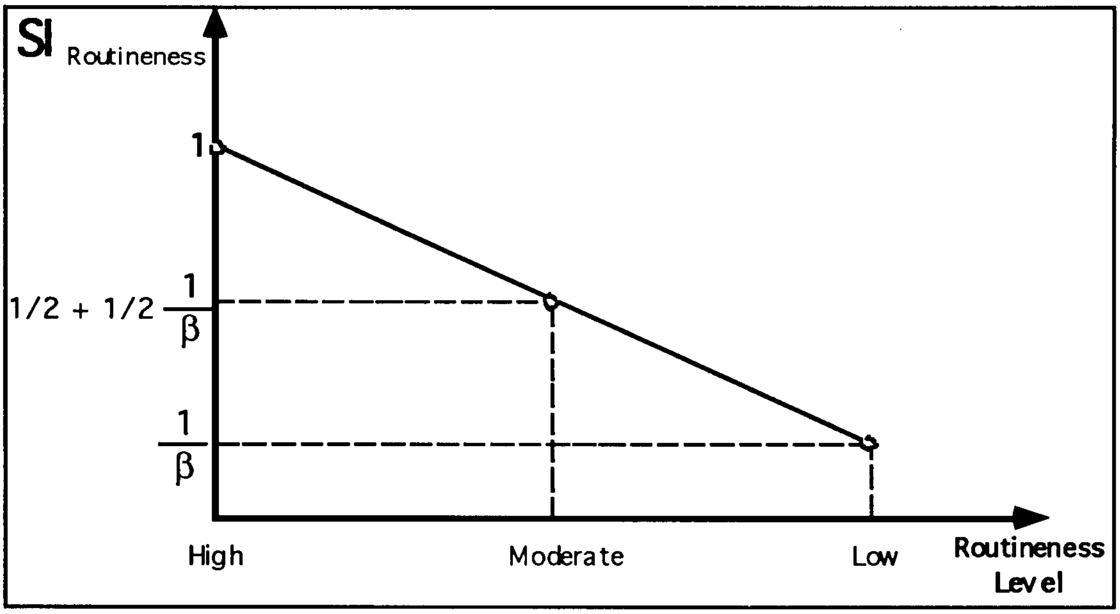

Figure C.3 - Linearized index measurement of routineness

$$SI_{Routineness|EDA_q} = \begin{cases} 1 & \text{if "high"} \\ 1/2 + 1/2(1/\beta) & \text{if "moderate"} \\ 1/\beta & \text{if "low"} \end{cases} \tag{C.9}$$

where b is the maximum degree by which routineness is judged to be increased for EDA_q.

The *system safety index* ($SI_{System,EDAq}$) of Equation C.1 measures the ability of the operator to properly acquire, assess, and act on information provided by the operating system. Similar to the quantitative calculation of stress and routineness, judgments are made as to the impact of system factors upon the overall safety index. The linearization is shown in Figure C.4 and formalized in Equation C.10.

$$SI_{Syst|EDA_q} = \begin{cases} 1 & \text{if "low"} \\ 1/2 + 1/2(1/\gamma) & \text{if "moderate"} \\ 1/\gamma & \text{if "high"} \end{cases} \tag{C.10}$$

where g is the maximum degree by which system complexity is judged to be increased for EDA_q.

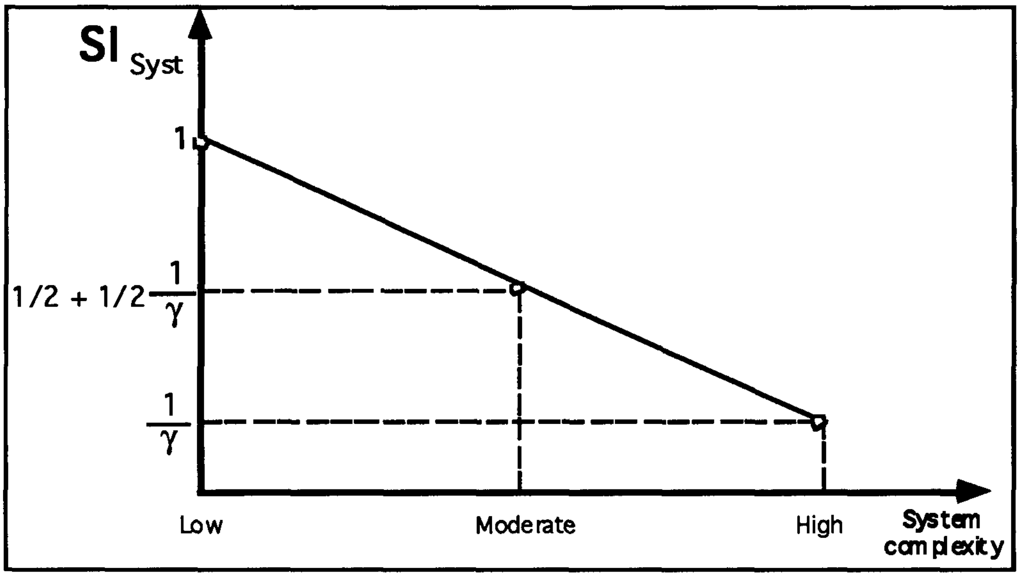

Figure C.4 - Linearized measurement of system complexity

The *environmental safety index* ($SI_{Environ,EDAq}$) in Equation C.11 is the product of two indices: the *external operating condition impairment index* ($SI_{External,EDAq}$) and *internal operating condition impairment index* ($SI_{Internal,EDAq}$).

$$SI_{Environ,EDA_q} = SI_{External_u,EDA_q} * SI_{Internal_v,EDA_q} \qquad (C.11)$$

The impacts of environmental factors in HESIM represent external and internal impairment contributors. Environmental factors impair the individual operator's ability to think and perform actions. Any combination of environmental factors may affect the abilities of the operator. However, any number of environmental factors may be the dominant contributors to errors.

For example, fire and smoke may be impairing the abilities to evoke mitigation procedures. However, smoke may be the dominant environmental factor leading to errors by the operators due to the operators inability to breath correctly. It is at the discretion of the user to determine degree to which a single environmental factor, or any combination of factors, affects the environmental safety index. This may be performed by a linearization method similar to the safety indices developed for stress, routineness, and system complexity factors developed above. As shown in Figure C.5, "high", "moderate", and "low" environmental impairment severity affect the accident contributors. Equation C.12 is the linearization equation used to determine the environmental safety indices.

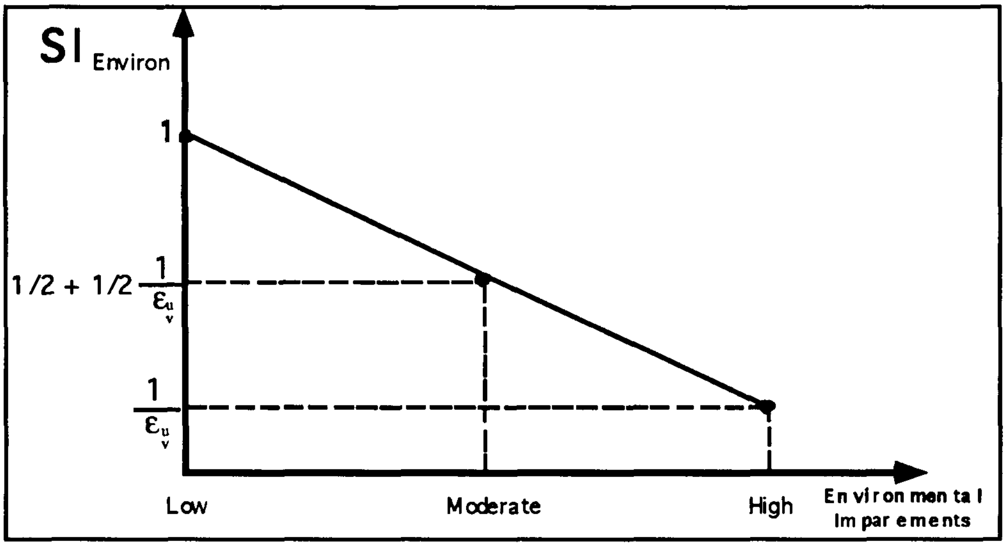

Figure C.5 - Linearized measurement of environmental impairment factors

$$SI_{\text{Environ}\left(\substack{\text{Ext}_u \\ \text{Int}_v}\right),\text{EDA}_q} = \begin{cases} 1 & \text{if "low"} \\ 1/2 + 1/2(1/\varepsilon_{u,v}) & \text{if "moderate"} \\ 1/\varepsilon_{u,v} & \text{if "high"} \end{cases} \qquad \text{(C.12)}$$

where e is the maximum degree by which external environmental factor u (e_u) or internal environmental factor v (e_v) is decreased for EDA_q.

The final step in the model development procedure is to relate the safety index evaluation to the overall reliability of the operating system. Figure C.6 provides an overview of the HOE evaluation procedure. Step 1 entails the system analysis procedure used to define the particular human, organizational, system, procedures, and environmental contributors to an accident scenario. The modeling procedure described was to use influence diagrams to develop an accident template that retains the primary causative mechanisms to an accident scenario yet does not entail many of the unique characteristics of the casualty being modeled

For Step 2 HESIM is used as a quantitative measuring procedure that incorporates both available accident data and heuristic judgments. As data becomes more available, there is a reduction of reliance upon judgments and experiences and a greater reliance is placed upon objective data to generate human error related probabilities.

Step 3 entails using the safety index evaluations for both calibrating and confirming the HESIM procedure. Historical failure rates for catastrophic events are used for confirmation of the modeling procedure and the HESIM is used to ensure that the quantitative modeling procedure is consistent with case

study analyses. Once the safety (or risk) indices are evaluated for the HOEs using the HESIM, they are input into the influence diagram template model. An overall safety index is calculated for the target failure event being modeled (e.g. grounding or collision for a tanker, loss of fuel containment on production platform) such that:

P_f = Probability of "Activity" results in undesirable outcome

As shown in Figure C.6, the safety index is then compared to the probability of failure for that particular accident event. This procedure is then repeated for a sufficient number of cases to determine a general range for the functional relationship between the safety indices and the failure event probabilities (Figure C.7).

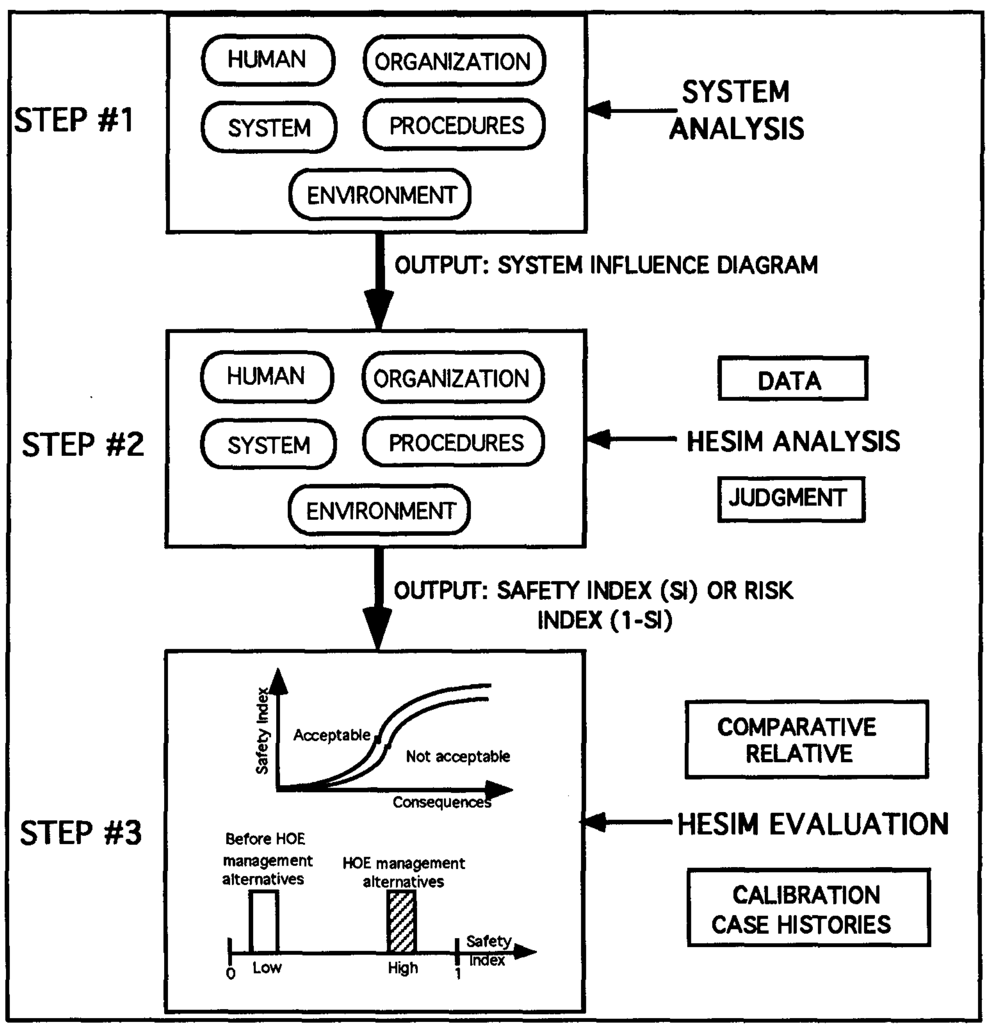

Figure C.6 - HOE analysis procedure based on HESIM indexing method

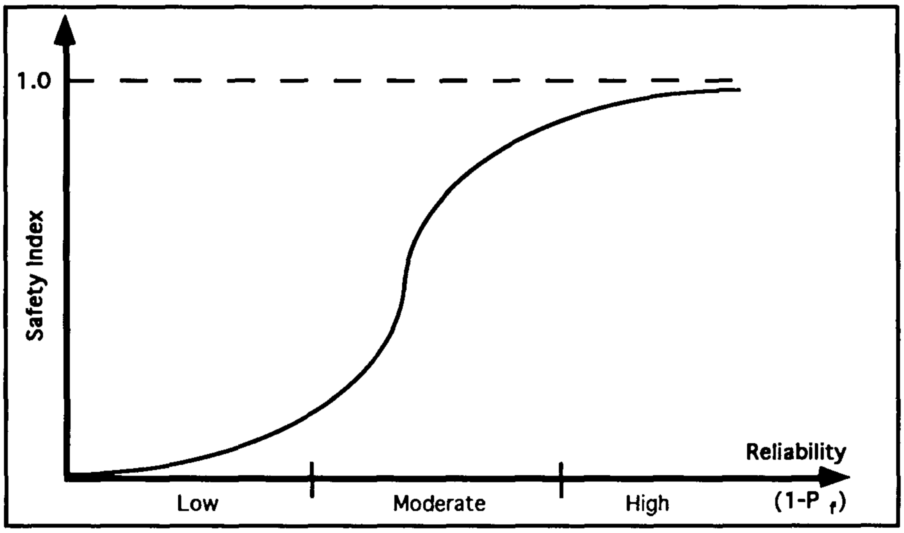

Figure C.7 - Probability-risk index relation curve

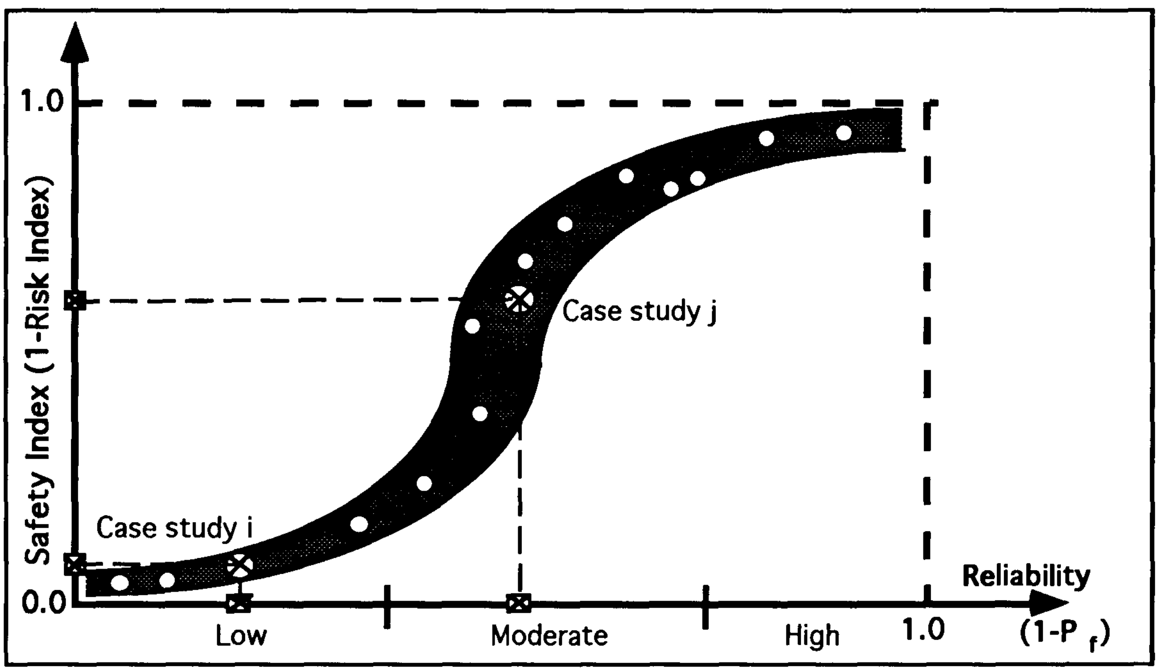

Figure C.8 - Safety index-reliability curves

As shown in Figure C.8, a risk meter can be developed that compares the safety index and the reliability of the operational system. The risk of failure can be categorized into "low", "moderate", and "high" intervals. The threshold values between high, moderate, and low (or unacceptable, marginal, and acceptable) risks are dependent upon the failure event, the consequences of that failure, and society's willingness to accept the risk.

Comparison between the safety index-reliability curves and probability-consequence curves for undesirable outcomes is performed to determine the relative risk to the undesirable outcome being modeled. This is expressed diagramatically in Figure C.9 where the risk index-reliability curve is compared with the reliability-consequence curve.

Further evaluation of the models are performed to assess management alternatives to prevent and mitigate the impacts of HOE related factors. This is performed to determine if the impact upon the system will increase the reliability of the system such that the risk becomes acceptable. This can be expressed diagramatically in Figure C.9 where the risk index-probability curve is compared with the probability of failure acceptability curve.

There is a six step approach to confirmation of the modeling procedure and the HESIM to both assess the risk of a particular undesirable target event and generate the safety-reliability curves shown in Figure C.9. The approach is as follows:

(1) Determine the threshold probabilities between acceptable, marginal, and unacceptable risks for the operation being modeled. These can be done through judgments, historical data comparison, financial settlements for prior casualties, etc.

(2) Determine the probability of the target event being modeled through judgment or historical data.

(3) Using the post-mortem study data, calculate the human error safety indices (risk indices) under the specific operating conditions using HESIM. Input the human error indices into the influence diagram template model representing the particular characteristics of the scenario being modeled.

(4) Calculate the risk index for the undesirable target event by reducing the IDA.

(5) Compare the results of the risk index with the target event probability. If the risk index and probability of the target event are consistent with case study implications, continue.

(6) If the safety index and probability of failure are inconsistent, calibrate the HESIM to attain consistency of results. This can be conducted by reexamining the impact of error contributors or further detailing the model.

(7) Repeat Steps 1-6 for other case histories to develop more reliable results.

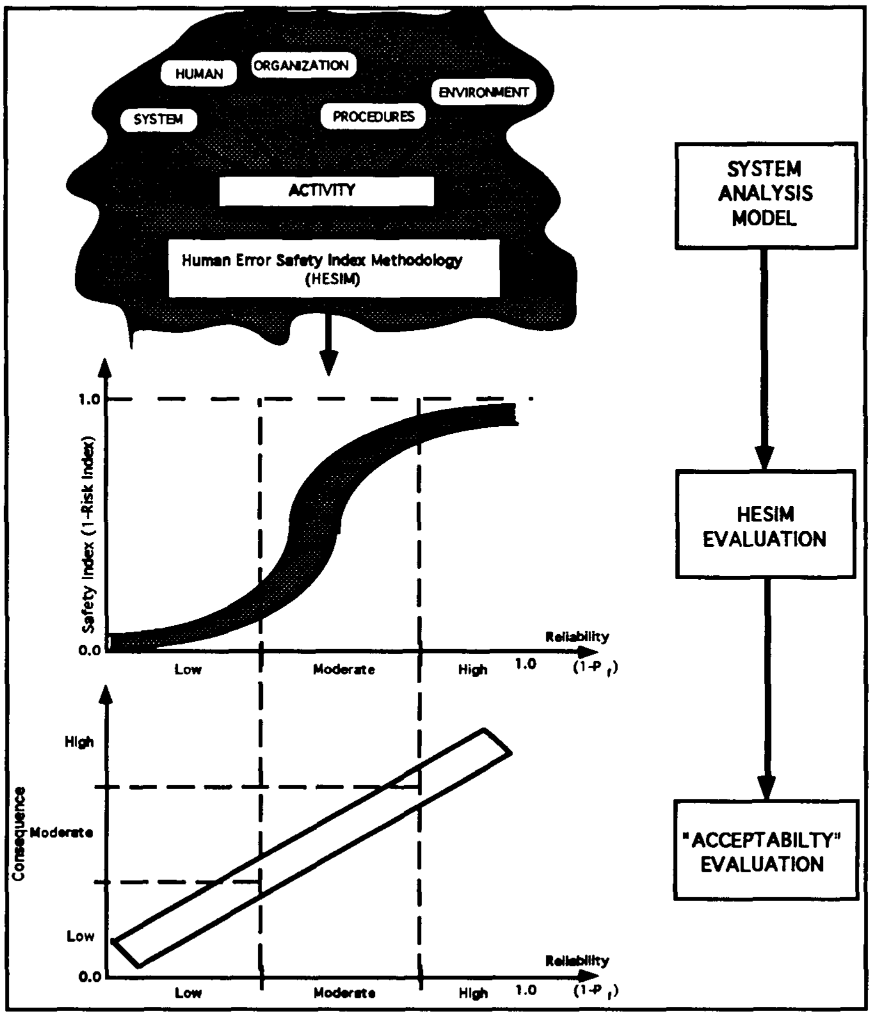

Figure C.9 - Safety index-probability-consequence curve comparisons for acceptable risk determination

Status

User interactive, windows oriented, spreadsheet based software has been developed to facilitate performing HESIM operations evaluations and risk index calculations. Extensive documentation including example applications has been developed to guide evaluations of operations related hazards associated with ships and offshore platforms [Moore, Bea, 1993].

A field testing and development project was initiated during 1993. The objectives of this two-year project are to further develop and verify the HESIM algorithms, to demonstrate its application to loading and discharge operations associated with commercial crude carriers, and provide initial calibration of its quantitative results.

This project also involves review and assessment of existing databases that contain information on tanker loading and discharge accidents. This

review is expected to lead to definition of improved database formats that can be used to supply quantitative and qualitative information for HESIM evaluations of this type of ship operation.

FLAIM

FLAIM (*Fire and Life safety Assessment Indexing Method*) can be described as a quantitative SIM in which selected key factors relevant to fire safety and life safety are identified, assessed and assigned numerical (weighting) values [Gale, et al. 1994]. Risk contributing factors are indexed and ranked using a weighting system algorithm, keyed to relative (comparative) risk, to yield a set of risk indexes, and an overall risk index for topsides facilities. For familiarity and ease of use, an academic letter grading scheme (A, B, C, D, F) based on a 4.0 grade-point scale was selected as the framework for assessing risk contributors.

Key topsides risk factors, identified on the basis of scenario analysis, expert opinion, and historical records, are selected and evaluated by the user together with provided or planned-for risk reduction measures. Life safety is assessed independently from fire safety, using risk factors specific to each, but accounting for their close interdependence . The adequacy of risk reduction measures and the overall platform Safety Management System (SMS) can be assessed by calculating the RIRA (*RIsk Reduction measures Assessment*) and SAMSA (*SAfety Management System Assessment*) indexes. These indexes reflect provision of risk mitigating and safety management status of the facility. They are combined with fire safety and life safety indices in order to arrive at an overall *topside risk assessment index.*

The FLAIM assessment procedure is outlined in Figure C.10. There are eight separate risk assessment modules, each of which yield individual risk indices used to calculate an overall Topsides risk index, drive FLAIM's algorithm. The titles of the modules are summarized in Table C.4

Table C.4 - FLAIM's risk assessment modules

• General Factors Assessment (GEFA)	• Operations and Human Factors Assessment (OHFA)
• Loss of Containment Assessment (LOCA)	• Risk Reduction Measures Assessment (RIRA)
• Vulnerability to Escalation Assessment (VESA)	• Life Safety Assessment (LISA)
• Layout and Configuration Assessment (LACA)	• Safety Management Systems Assessment (SAMSA)

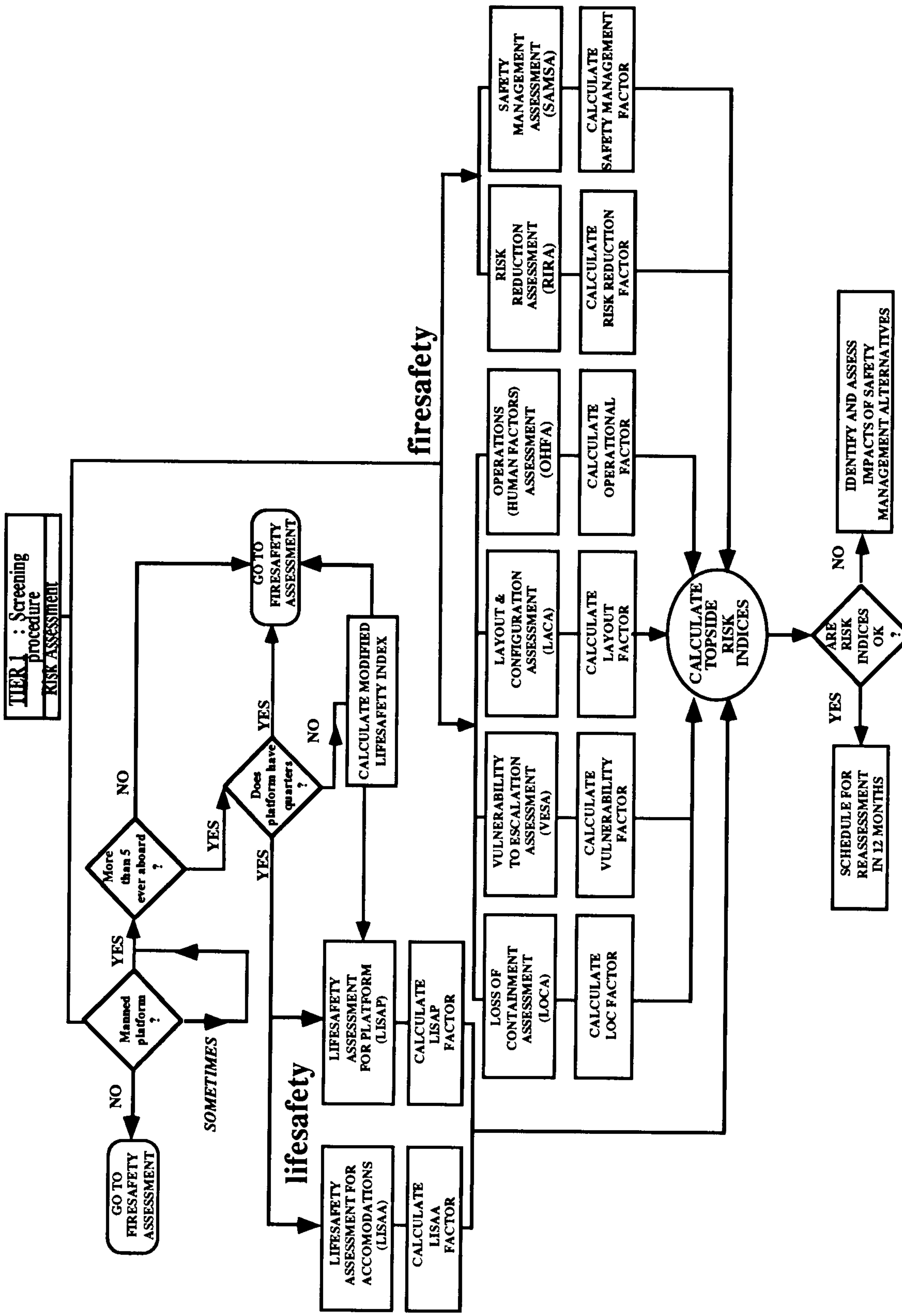

Figure C.10 - FLAIM assessment procedure and modules

Two of the FLAIM modules are of particular interest to this project. The Operational / Human FActors Assessment (OFHA) module and the Safety Management System Assessment (SAMSA) module. These modules attempt to capture the essence of HOE as they affect offshore platforms. These will be defined in the next two sections.

Operational Human Factors Assessment (OFHA)

Errors involving operational activities are considered to constitute the single most important class of risk contributors leading to platform fires, explosions, and loss of life. Many individual factors contribute to this problem including fundamental deficiencies in organizational aspects of the management structure. In OFHA, FLAIM seeks to identify those normally encountered production activities which may involve either an inordinate reliance/dependence on human judgment to avoid serious consequences (direct-link couplings), or activities in which the risk of error is compounded by the complexity or multiplicity of the tasks involved, e.g., multiple simultaneous operations such as drilling, producing and maintenance involving hot work or startup of equipment.

The OFHA risk assessment module contains approximately 167 questions covering five subcategories (Figure C.11):

- Maintenance and Repair Work (MARW),
- Multiple Operations Assessment (MULOPS),
- Operational Management Of Change (MOCOPS),
- Assessment Of Operator Dependence And Response (OPSDAR), and
- Operational History (OPHIST).

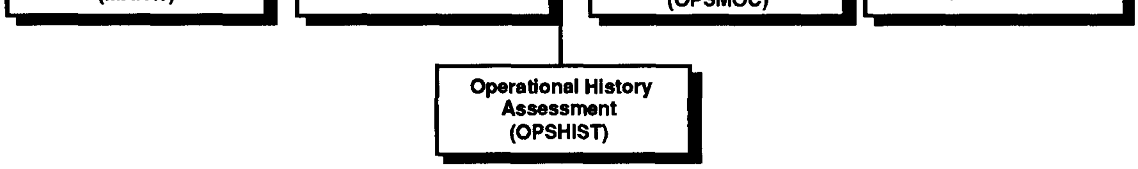

Figure C.11 - Components of the operational human factors assessment - OFHA

MARW addresses operational risks during times when maintenance and repair activities are taking place on the platform -- a time when many accidents happen. These activities include:

- major renovations/additions,
- turnarounds
- routine maintenance/repair work involving equipment entry, line-breaking, and hotwork
- pipeline pigging/scrapper work
- downhole wireline work such as removing and testing storm chokes
- workover operations
- specialty work, such as pipeline riser retrofits/additions, control system modifications necessitating temporary bypass of safety shut-down functions, fire protection system work causing temporary impairment of the protection systems

Often times MARW activities involve "line-entry" or "vessel-entry" procedures whereby the risk of an loss of containment event is increased. Normal process control elements, pressure relief valves, emergency shut down valves, and other control and safety provisions may be placed in a bypass mode or be removed from the system, thereby increasing the potential vulnerability to an initiating event. Hot work involving welding, cutting, grinding, etc. is also commonly included, resulting in increased ignition risk.

During MARW, reliance on human intervention and judgment is greatly increased over that required for normal operations -- both from a preventative and a response standpoint. More things can go wrong, and there is a greater dependency on worker judgment to make the correct decisions. However, there is also a greater risk of error during such activities, especially so when non-routine operations are involved, job complexities are increased, and work crews may be diverse and unfamiliar with the facilities or inadequately trained in the particular operations taking place.

The criticality of any particular MARW activity has been distinguished into four major categories:

- process critical,
- process non-critical,
- non-process critical, and
- non-process non-critical.

Process critical operations are considered to be those activities that involve vessel and/or line entry into hydrocarbon handling systems and equipment, e.g., operations posing an immediate risk of Loss Of Containment (LOC). This includes all topsides process systems in which crude oil, natural gas, natural gas liquids (condensate) liquefied petroleum gases, and imported flammable liquids (methanol, glycol, aviation gasoline, etc.) are either processed, treated or otherwise handled/stored.

Process non-critical operations are considered in FLAIM to involve equipment and systems that handle non-volatile, combustible liquids (flash points above 140°F) at or near atmospheric pressure, such as fuel oil, diesel fuel, and lubricants.

Non-process critical operations are those activities that impact a platform's ability to respond to an LOC event, including fire and explosion, or that increases the risk of ignition should an LOC event occur. Any hot work activity not involving process critical activities would fall into this category. In addition, work that would require deactivation of any safety system, such as a fire or gas detection (as may be necessary during hot work), a fire pump, or a deluge system, is included herein.

Non-process non-critical work are considered in FLAIM to include those routine maintenance and repair activities, e.g., chipping and painting, that do not directly increase LOC risk, but by their very presence onboard, may add to platform supervisory and manpower demands, thereby contributing to overall increase in platform risk during simultaneous operations.

In OFHA, FLAIM recognizes that platform operational risk levels are time dependent, varying in both the long term, e.g., emerging safety deterioration trends, and in accordance with the nature of daily operations. MULOPS assesses the frequency and nature of those simultaneous activities that produce short periods of high operational risk.

Simultaneous operations are, in general, significant risk contributors depending on the nature and number of simultaneous operations occurring; this is especially true whenever downhole work is in progress on live (capable of flowing) wells. Large platforms may have several contractor crews engaged in different construction/maintenance activities at the same time, and while normal production and drilling activities are also taking place.

MULOPS seeks to evaluate the relative risk of simultaneous multiple operations by establishing their nature, relative proximity to each other, and the frequency of their occurrence. Simultaneous operations during production may include drilling, workovers, wireline operations, refueling of onboard fuel supplies, off/onloading bulk supplies, pig launching and receiving, and various construction and maintenance activities, such as installation of riser safety valves.

The extent to which operational safety and the control of emergency situations depends upon operator response is an important risk consideration. Platform process systems designed with protective systems that automatically sense and initiate corrective actions to developing emergency situations are apt to be less vulnerable to errors in human judgment or lack of prompt operator response. OPSDAR seeks to evaluate the extent to which the platform design and operational scheme places reliance on operator response and judgment in order to safely shutdown topside systems and respond to LOC events.

Cognitive and sensory limits of operator response becomes increasing important in accident causation as the demands placed on operators increase. This problem is much the same faced by military fighter pilots who, compared with their immediate predecessors, have both a much greater array of sensory information to deal with as well as a much short time in which to arrive at correct decisions (due to higher flying velocities). The 1979 Three Mile Island nuclear plant accident was largely a result of a failure to properly sort out and recognize critically important information during the developing crisis scenario.

OPSDAR uses a what-if scenario based approach to determine if emergency response plans are inadvertently placing too much reliance on operators performing critically important tasks or otherwise (overburdening) platform personnel to ensure safety. For example, OPSDAR asks if platform blowdown system valves are automated or if operators must manually open them to depressure system piping; are platform deluge systems automatically actuated or must operators manually open local control valves; are deluge systems provided or are operators expected to fight fires manually with hand-hose lines, etc.

FLAIM includes a component intended to identify endemic operational problems as may be evidenced by reoccurring accident events. OPHIST addresses the operational history of the platform and seeks to determine if certain types of operational related events are more prone to occur. This information is intended to distinguish between appropriate changes that may need to occur and those that may have already been implemented to rectify the root cause of such events.

Safety Management System Assessment (SAMSA)

The SAMSA module contains those factors identified as being most prevalent in failures of the Safety Management System. SAMSA seeks to assess the adequacy of management's ability to identify and respond to root-cause errors stemming from human and organizational factors. Thirteen error classifications have been identified in the HOE taxonomy developed by Moore and Bea [1993]. These classifications have been subdivided into four general categories, all of which are subject to external environmental influences.

In FLAIM's SAMSA risk module, factors identified in the HOE taxonomy are accounted in the four subcategories:

1) Management Systems (MASA),
2) Fire (Emergency) Preparedness (FIPA),
3) Safety Training (SATA), and
4) Management of Change Management Program (MOCMAP).

The components of the SAMSA risk evaluation module are illustrated in Figure C.12.

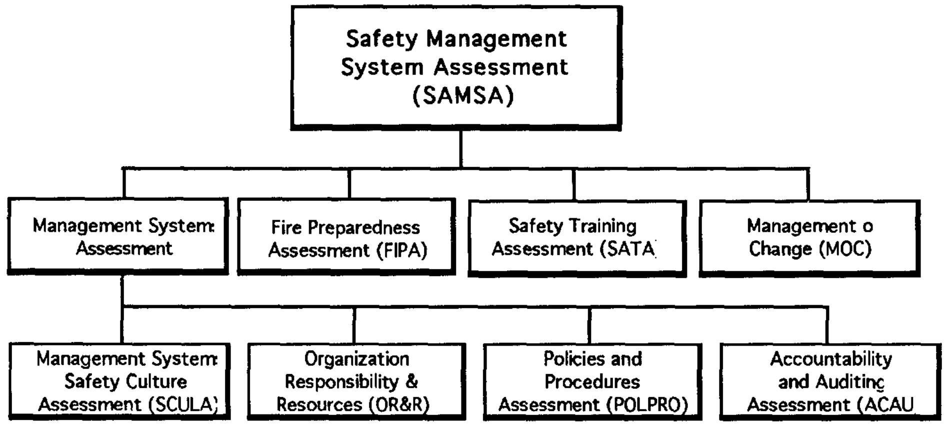

Figure C.12 - Safety Management System assessment module components

MASA is further subdivided into four separate risk assessment sections:

1) Management Systems Safety Culture Assessment (SCULA),
2) Organizational Responsibility & Resources (OR&R),
3) Company Policies and Procedures (POLPRO), and
4) Accountability & Auditing (ACAU).

Each of these components of SAMSA are considered to be interdependent and essential to achieving fire and life safety operating goals.

The four MASA components component of SAMSA form a synergism that are, in fact, a compilation of the (fourteen) essential elements of Total Quality Management (TQM) as expounded by Deming. These elements are the sole responsibility of top management and can only be carried out by top management; they serve as direct indicators of management's awareness of and commitment to continued safe operations.

The most essential element stressed by Deming in his fourteen point approach to TQM is his last program element -- creating a structure and environment in top management that is conducive to continually *cultivating* and building upon on the other thirteen points, e.g., develop a "corporate culture" of quality that permeates down and throughout the entire organization. Deming believed in the need to develop a "constancy of purpose towards improvement" in which management's philosophy embraces bold (new) concepts aimed at empowering the worker, creating organizational incentives encouraging and rewarding self-improvement, eliminating worker fear (to do the right thing) and removing barriers to improving quality and safety, e.g., imposed production quotas.

The SCULA section of MASA, together with OR&R and the other Management System components, identify and assess key indicators of management's awareness and commitment to these ideals.

Organization Responsibility and Resources (OR&R) seeks to identify weak safety culture environments by asking questions about: the company's safety and loss prevention staff relevant to the number of platforms beiinstructions on how to achieve those goals, the course of platform safety goes uncharted. Company Policies and Procedures (POLPRO) asks if the platform operator has a written policy establishing definitive safety objectives, goals, practices and the means to monitor, measure, and improve meeting safety targets.

The POLPRO element of MASA accounts for the status of written, up-to-date operating instructions for all topside systems and process components, including startup procedures, normal and temporary operations, emergency operations including emergency shutdowns (for each level of shutdown), and black-start restarts from complete shutdowns of all platform operations and power sources. Individual startup/shutdown and operating instructions for pumps, compressors, fired heaters, should be explicit to the machine in its "as-built" (as-installed) condition.

A written Safe Work Practices (SWP) Manual should cover many routine tasks including: line and vessel opening/entry operations, lockout and tagout procedures, confined space entry, hot work and cutting operations, inerting and purging practices, heavy lifts and crane operations, sampling and sample connections, opening of drains and vents, use of personal protective clothing and gear, etc. The Permit to Work procedure should be clearly explained both in concept and in explicit requirements. In addition, accident investigation instructions and forms may be included in the SWP manual or provided as a separate document in the emergency response plan. These issues are addressed by the POLPRO component of MASA.

Emergency Response Plans are also another important element included in POLPRO. Most platforms will already have written plans for oil spills and for emergency evacuation as required by MMS and the USCG. POLPRO seeks to assess the adequacy of these procedures and asks about the frequency of emergency response drills and the provision of improving written plans based on feedback from lessons learned in rehearsals.

Successful implementation of the platform's safety management program depends to a large extent on the means used to measure progress in meeting safety goals and to effect improvements in program execution. Accountability is required to effect change and realize improvements. The ACAU element of MASA seeks to determine if the safety program is being effectively carried forward with the requisite level of management support and accountability necessary for meaningful implementation. This includes auditing of the safety assurance and written reports to management.

An important risk indicator in MASA is an operating company's "lessons-learned" program. ACAU asks the operator about the disposition of information collected in near-miss and accident reports. A pro-active approach taken in analyzing and learning from operational experiences, and then following through by communicating this information and revising company practices accordingly, is one indicator of a strong safety culture. Conversely, compliance with accidents report requirements as mandated by MMS OCS Orders and committing the information to a file cabinet without further thought is clear evidence of a "compliance mentality" as described by the CAI.

The FIPA component of the SAMSA risk assessment module seeks to measure a operating crew's preparedness and ability to effectively deal with developing emergency situations. FIPA does not address hardware aspects of preparedness; these are accounted for in RIRA. FIPA is the complementary component to RIRA and evaluates the human and organizational factors deemed critical to controlling a developing fire scenario.

The extent of human intervention necessary to successfully control a developing situation depends to a large extent on the platform design, its susceptibility to loss of containment events, provisions for automatic detection, control, and shutdown, and the platform's inherent vulnerability, or conversely, its robustness to resist thermal impact. There are two terms in "the equation" for assessing fire preparedness, each containing several variables.

The first term evaluates management's understanding of exactly what role the crew is expected to play in any given emergency situation. The assessment seeks to address issues of response expectancy with a view to determining whether or not an unrealistic reliance and dependency has developed on a crew's ability to respond.

For example, identification of critical manual tasks necessary for successful fuel-source isolation in a LOC event, when compared to concurrent demands for fire-fighting, communications, and general platform shutdown, may show an inordinate dependence on human response in some scenarios. Quite often, emergency demands placed on crew members tend to evolve and change in response to platform modifications and expansions. The cumulative effect may exceed reasonable response expectancies, but go unrecognized for lack of an emergency operability study.

The second term in the fire preparedness equation addresses the crew's preparedness and capability to carry out those essential demands placed on it under various emergency scenarios, assuming the demands are reasonable as evaluated above. This requires and assessment of the crew's knowledge and understanding of what is expected for a given situation, their ability and willingness to effect their duties, and the capability to demonstrate this through hands-on hypothetical training exercises for emergency situations.

The Safety Training Assessment (SATA) component of the SAMSA risk module is intended to evaluate the overall level of formal personnel training and operator qualifications. Recognizing that human and operational error is the primary cause of offshore accidents, the adequacy of training at all levels throughout the organization is assessed -- both from an operational standpoint and from a risk aversion/cultural standpoint.

In the Management of Change Management Program (MOCMAP) section of the SAMSA risk module, FLAIM asks if the prerequisite elements of a MOC management program, as identified by accepted codes of practice for the operations of offshore platforms are established and implemented in written procedures. This should include the requirement for a hazards analysis of the safety, health and environmental implications of the proposed change, including its direct local impact and global ramifications to the overall risk level of the platform. Such an evaluation may be performed by using FLAIM's methodology to assess these impacts.

The FLAIM Algorithm

FLAIM's input data is requested in one of three primary forms: (1) binary, (2) qualitative letter grades, and (3) numerical values. The following is an explanation of these input values.

Binary Input Data. The binary value system (β_{ij}) is presented by answering "Yes" or "No" (or "Good" or "Bad") to the presented questions. The input value returns a value of 0 or 1 dependent upon the assignment of the value to the answer (Eqn. 1). Any question that is to be answered "Yes" or "No" in the FLAIM spreadsheet program is followed by - "(Y/N)."

$$\beta_{ij} = \begin{cases} 0 \text{ if "Yes"} \\ 1 \text{ if "No"} \end{cases} \quad \text{or} \quad \beta_{ij} = \begin{cases} 0 \text{ if "No"} \\ 1 \text{ if "Yes"} \end{cases} \tag{C.13}$$

for question i, assessment j.

Letter Grades. The grade point structure follows along the line of the grade point structures used in academia. The grade points range from "A" to "F" and are assigned numbers based upon the same 4.0 point grading system used in many academic grading schemes. The algorithm automatically assigns a numeric value to the grade point input provided by the user in the spreadsheet (Table C.5). Questions that directly use the grade point scheme in the spreadsheet are provided with a short description of what constitutes the selection of that grade. The grades are represented by $0 \leq \eta_{ij} \leq 4$ (risk assessment i, question j).

Table C.5 - Grade point scheme for platform risk factors and corresponding numeric values

A	- "Excellent" condition of the risk contributing factor upon the platform fire and/or life safety **(4.0)**
B	- "Good" condition of the risk contributing factor upon platform fire and/or life safety **(3.0)**
C	- "Fair" condition of the risk contributing factor upon platform fire and/or life safety **(2.0)**
D	- "Poor" condition of the risk contributing factor upon platform fire and/or life safety **(1.0)**
F	- "Bad" condition of the risk contributing factor upon platform fire and/or life safety **(0.0)**

Numerical Values. Quantitative values (such as barrels of oil per day (BPD), millions of standard cubic feet of gas produced per day (mmscfd), size of operating crew, etc.) are numeric value inputs. The units prescribed for each input value is provided at the end of each question. This information is used in the assessment of the relative overall consequence level of the platform, as well as for evaluations of specific risk contributing factors.

Weighting Structure. To maintain consistency with the grade point scheme, all default input values are considered to range between 5.0 and 1.0. This is equivalent to the concept of the number of "units" that an academic course is worth. The greater the unit value, the greater the relative importance of that factor to the grading scheme.

The weighting structure of FLAIM's algorithm has two types of value inputs (ω_{ij}) (risk assessment i, question j): (1) direct input value assessment of weighing values, and (2) indirect input value assessment, e.g., values generated as part of the algorithm. Direct inputs are provided by the user's assessment of the relative importance of that particular factor to fire and life safety on any given platform.

Indirect value assessments can be made through summing the binary input values (β_{ijk}) which are made up of sets of sub-questions. There can be between 2 and 23 sub-questions dependent upon the importance of the factor in question to fire and/or life safety.

Indirect value assessments are also functions of the numeric input values. These values are used to weigh the relative importance of fire and life safety risk. For example, if there is a small crew contingent aboard the platform, there is a smaller overall risk of injury or loss of life to personnel than if there was a large operating crew. Or, for example, production rates (high or low) may have a great impact upon the loss of containment risk.

Value Structure. The primary algorithm structure is in the form shown in Equation C.14. This general algorithm structure is similar to that of the academic grading scheme shown in Equation C.13. The *grade point average* (GPA) is determined by summing the product of the grades and credits for each course (total of *p* courses) and dividing by the total number of credits. This value is the GPA.

$$\eta_j = \frac{\sum_i^n \omega_{ij} \eta_{ij}}{\sum_i^n \omega_{ij}} \tag{C.14}$$

$$GPA = \frac{\sum_l^p Credit_l \, Grade_l}{\sum_l^p Credit_l} \tag{C.15}$$

Numeric Value Range Assignments. The numeric value assignments have a pre-defined "value range" that determine the grading structure. Single-question numeric value assignments have direct value assignments. Multiple-question numeric value assignment questions use an averaging of values obtained from each sub-question. As already explained the user is asked to determine the range values that determine the grading structure based on the particular platform design and operation circumstances under scrutiny; FLAIM has been intentionally designed to allow either the user, or the consensus of a user's group, to "calibrate" the risk assessment process.

Binary Value Assignments. The binary input value assignments are given dependent upon whether the question has a positive or negative impact upon fire and life safety values. Multiple-binary value assignments are averaged over the sub-questions to provide an overall grade for that particular question.

Grade Value Assignments. Single grade value assignments are based directly upon the A-F structure described in Table C.5. The multiple sub-question value assignments use the A-F grading scheme. Similar to the numerical and binary multiple sub-question value assignments a mean grade value is used by averaging the grade over the number of sub-questions.

Question Weighting Assignments. In accordance with Table C.6 default values are assigned to the weight of each question dependent upon the level of the assessment. Certain FLAIM questions have already been pre-determined as suggested red-flag or "red-level" questions. These questions have been deemed to be particularly important to the safe operations of any offshore platform. Weighted value assignments for these factors are assigned by the user; those questions identified of particular importance may be assigned

weighting values greater than those assigned at the Tiers 1-3 levels. However, FLAIM also allows the user to reassign the suggested default value of any selected question. If the assigned value exceeds the Tier 1 level value of 5, FLAIM automatically designates the question to a "red-level" status.

Factors from Tier 1 (initial screening) assessments are assigned the highest weighted values since they account for the most important contributing fire and life safety factors specific to the platform being assessed.[1] More detailed Tier 2 and Tier 3 questions are weighted correspondingly lower to reflect their relative importance to overall fire and life safety.

Table C.6 - Value Weighting Assignments According To Relative Importance

Relative Importance of Assessment to Fire or Life Safety	Assessment Level Assignment	Default* Weighting Value Assignment - ω_{ij}
Red-Level	Initial	Assigned by users
High	Tier 1	5 (5-4)
Moderate	Tier 2	3 (3-2)
Low	Tier 3	1 (2-1)

* Values in parentheses are value assignment ranges for each assessment level.

Though default values are assigned, FLAIM allows users to modify the value to reflect their preferences and experiences. Should a Tier 2 or Tier 3 factor be assigned a higher weight value comparable to that at a level higher than originally assigned, the user may reevaluate whether that contributing factor should be reassigned to a higher Tier level. At the user's discretion, these values may be changed to account for the relative importance of the question as determined by a consensus of the user group performing the analysis.

Individual FLAIM Assessment Grades. Equation C.16 is used to determine the GPA for any assessment j (η_j). As shown in Equation C.18, the grade value is assigned according to the question type. Each question is weighted according to its Tier level assignment except for the critical level where the weighted value is assigned by the users (τ_{ij}).

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[1] The basic difference between red-level and Tier 1 questions is that the former are considered to be questions which are generally important to the operations of <u>all</u> offshore structures, whereas Tier 1 level questions may be <u>specific</u> to the platform being analyzed

[3] x^t_{ij}: pre-defined range value for question i, assessment j, and range value t

[4] y^t_{ijk}: pre-defined range value for question i, assessment j, sub-question k and range value t

$$\eta_j = \frac{\sum_i^n \omega_{ij}\eta_{ij}}{\sum_i^n \omega_{ij}} \qquad \text{(C.16)}$$

where

$$\eta_{ij} = \begin{cases} \xi_{ij} & \text{if question i, assessment j is single question numeric} \\ \delta_{ij} & \text{if question i, assessment j is sub-question numeric} \\ \beta_{ij} & \text{if question i, assessment j is single question binary} \\ \rho_{ij} & \text{if question i, assessment j is sub-question binary} \\ \varepsilon_{ij} & \text{if question i, assessment j is single question grade value} \\ \gamma_{ij} & \text{if question i, assessment j is sub-question grade value} \end{cases} \qquad \text{(C.17)}$$

$$\omega_{ij} = \begin{cases} \tau_{ij} & \textit{if} \text{ "Red-Level"} \\ 5 & \textit{if} \text{ Tier 1} \\ 3 & \textit{if} \text{ Tier 2} \\ 1 & \textit{if} \text{ Tier 3} \end{cases} \qquad \text{(C.18)}$$

FLAIM's Overall Fire and Life Safety Index

To determine the platform's overall Fire and Life Safety Index a weighted sum of all risk assessment modules is made to determine the index value. Equation C.19 is the weighted assessment used to calculate the overall Fire and Life Safety Index. The weighted assessment procedures allows the user to take into account the overall relative importance on any single risk assessment module relative to each other, e.g., how GEFA, LOCA, VESA, LACA, OHFA, RIRA, LISA and SAMSA should be considered on a comparative basis.

$$GPA_{\text{overall}} = \textit{Overall Fire and Safety Index} = \sum_{j=1}^{5} \sigma_j \eta_j \qquad \text{(C.19)}$$

where

$$\sum_{j=1}^{5} \sigma_j = 1.$$

FLAIM calculates the overall Fire and Life Safety Index using equal weighting among all risk assessment modules as a default condition. This is in recognition of the need to assess each module's relative weighting value based on the particular platform under consideration; not because of any

implied level of equivalency. For example, on newer platforms the risk of LOC events due to mechanical failure may be judged to be relatively low, while the likelihood of a human error caused accident may be high due to simultaneous drilling, production, and construction activities. In this regard, it is important for the user to establish a uniform application of weighting values among groups of similar platforms in order to derive meaningful results from this procedure.

Status

User interactive, windows oriented, spreadsheet based software has been developed to facilitate performing FLAME evaluations and risk index calculations. Extensive documentation including an example application has been developed to guide evaluations of fire and explosion hazards on offshore platforms [Gale, Bea, Williamson, 1993].

A field testing and development project has been proposed (1994). The objectives of this project are to further verify the FLAIM algorithms, to demonstrate its application to assessment of a variety of offshore platform operations, and provide initial calibration of its quantitative results.

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Appendix D

EXAMPLE: PRA OF HOE IN DESIGN OF AN OFFSHORE PLATFORM

Introduction

This example was developed during the research project performed and reported by Paté-Cornell and Bea [1988, 1992]. The example addresses HOE in design of the structure for a conventional, steel, template-type, pile supported offshore platform (Figure D.1). It primarily addresses the organizational influences on the human related aspects of the reliability of the platform structural system. Design, construction, and operation life-cycle phases of the platform are evaluated with an emphasis on the design phase. The effects of checking in the design process are illustrated together with the effects of improvements in the QA / QC processes.

Three functions have to be performed by the platform structure: the anchoring provided by the foundation, the support from the jacket, and the drilling and production activities conducted on deck(s). The potential initiating failures are: failure of the foundation (O), failure of the jacket (A), and failure of the deck (E) (Figure D.1)

External loads such as waves are applied to the whole structure. Note that an initiating failure means that one of the subsystems fails before the others under external loads of given type and magnitude. The fact that the foundation failure constitutes an initiating failure under a particular level of wave load means that the capacity of the foundation is lower than this level of wave load, and that the capacities of the jacket

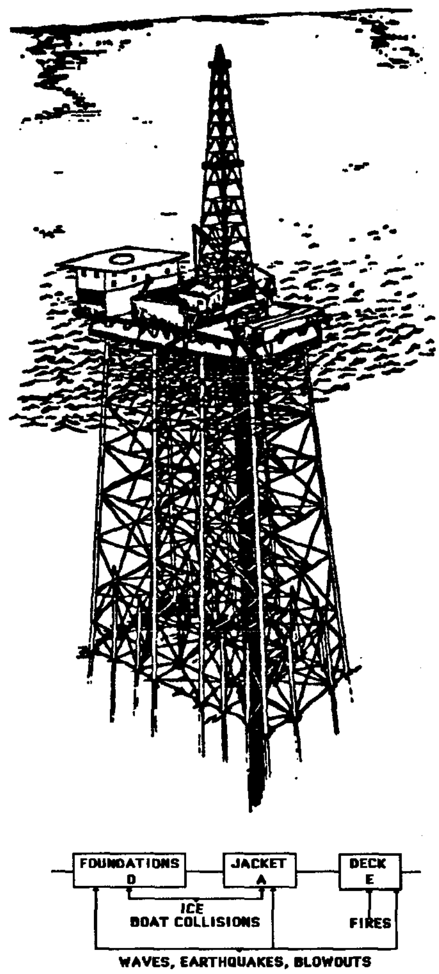

Figure D.1 - Analysis of components, functions and external events for an offshore platform

and the deck exceed that of the foundation. Therefore, initiating failures are mutually exclusive events.

Let w be a particular level of wave loads and $p(. \mid w)$ the failure probability of a given system conditional on w. The failure probability of the platform is therefore:

$$p(F \mid w) = p(O \mid w) + p(A \mid w) + p(E \mid w) \qquad \text{(D.1)}$$

The annual probability of failure of the structure subjected to these loads can be computed as the result of the *hazard analysis* (e.g., probability density function for the annual maximum wave height $f_W(w)$), and the *fragility analysis* above that reflects the capacities of the different subsystems to withstand these loads and is described by the probability of failure conditional on a given wave height ($p(F \mid w)$).

The overall failure probability can be written:

$$p(F)=\int f_W(w) \times p(F \mid w)\, dw \qquad \text{(D.2)}$$

Typical results of a PRA for a whole structure can be, for example: $p(F) \approx 10^{-3}$/yr. Explosions, blowouts, and fires cause approximately 80% of all failures. Within this class of external events, typical results show that the deck may fail first in two thirds of the cases, while, for the remaining third, the foundation and the jacket are equally likely to fail first. The rest of the failure probability is mainly due to excessive wave loads and can be allocated among failures of the jacket (≈15%), failures of the foundation (≈10%), and failures of the deck (≈5%).

Typical final results for annual failure probabilities based on a total failure probability $p(F) \approx 2 \times 10^{-3}$ are as follows:

p(Deck)	$= 10^{-3}$
p(Jacket)	$= 6 \times 10^{-4}$
p(Foundation)	$= 4 \times 10^{-4}$

The approach in this PRA evaluation of HOE in design of the platform structure is to compute a probability distribution for the structure system capacity based on an analysis of the occurrence, detection, and correction of HOE. The structure of the aggregation model is based on an ETA including the probability and the nature of errors in different subsystems, the reliability of the review process as a sequence of error signals that can be observed or missed, and the effectiveness of corrective actions.

This analysis yields a probability distribution for the capacity of the structure to withstand loads given its final state. PRA then allows computation of the probability of failure for each scenario of capacity and loads.

The first step is the identification of an exhaustive set of possible errors in the design, or the construction, or the operation of a platform and the assessment of the probability of each particular type of error. The second step is the computation of the failure probability of a particular member or subsystem given the occurrence of each type of error. This characteristic determines the level of error severity. The third step is the integration of this new failure probability (example, a particular member of the jacket) in the general PRA model in order to compute the effect of the design error on the overall reliability of the platform.

In this example the errors are combined into classes of severity. Their probability of occurrence and the probability of failure of the platform conditional on different combinations of errors are obtained, in this section, through encoding of expert opinion on the basis of several data sets. These data sets provide statistics about failure types and failure causes. Expert opinion is used to relate the error types (as defined in the taxonomy presented above) to the failure of the different subsystems and, therefore, of the whole platform.

Error Analysis: Occurrences and Types

In this example, the classification of HOE is divided into two basic categories of errors: gross errors and errors of judgement (Figure D.2).

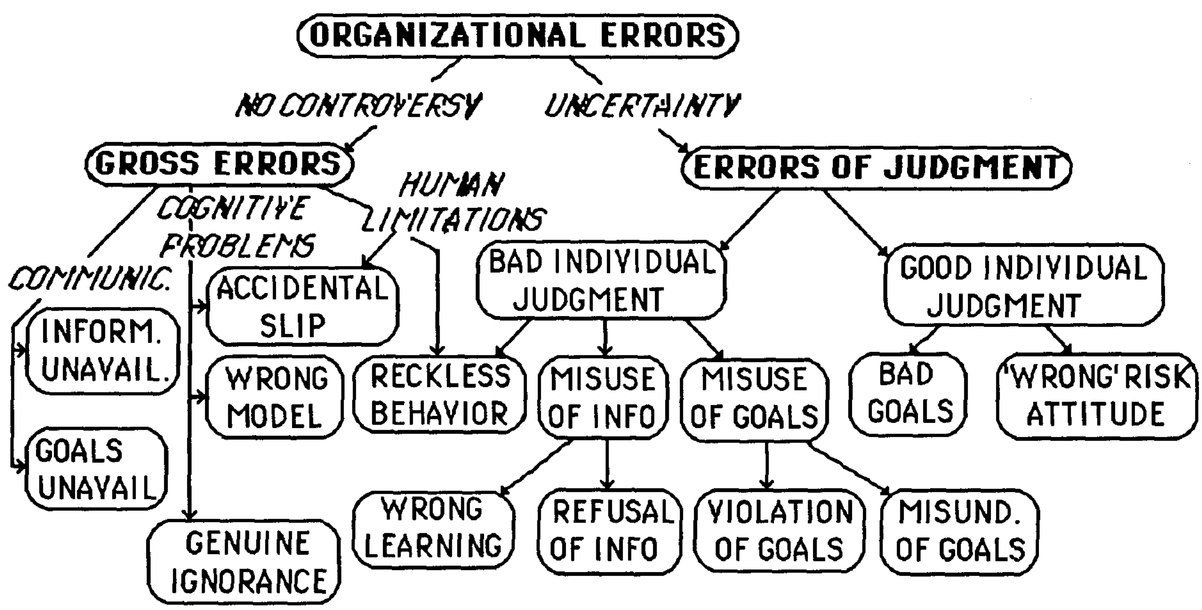

Figure D.2 - Classification of HOE used in PRA

Gross errors are defined as those that develop uncontroversial problems that come from a temporary or permanent lack of knowledge and understanding of a situation, or inability to respond under specific circumstances. A distinction is made among communication problems (either of goals or of information), cognitive problems, and problems due to human limitations.

Gross errors (as well as errors of judgment) can also be caused by human physical and psychological limitations. These errors may look like accidental slips or even "reckless behavior". The basic cause can be a combination of severe circumstances and/or physiological limitations and incapacity to deal with an unusual environment.

Errors of judgment are those that are open to interpretation, for two categories of reason: uncertainty about facts, and diversity of preferences in the face of uncertainty. Contrary to gross errors, they cannot be easily defined by a violation of a deterministic truth. Assessment of a probability or a probability distribution to describe, for example, uncertainties due to a lack of fundamental knowledge about a phenomenon generally requires a subjective input to interpret the evidence. As for risk attitudes and preferences in the face of trade-offs, they obviously vary among individuals and there is in principle nothing right or wrong about a particular risk attitude.

Bad judgment can occur in several different ways. First, the humans and organizations may simply violate the laws or the traditions of the profession or of society at large when making its safety decisions.

Second, the humans and organizations may be inconsistent in its risk attitudes across a spectrum of decisions under uncertainties involving comparable risks in different parts of the organization, for example, financial risks involved in technical failures versus economic risks due to market fluctuations.

Third, the humans and organizations may refuse to consider relevant available information and misestimate the risks which may result in a decision that appears risk prone. This may occur due to information problems such as inability of communicating incomplete information and resulting uncertainties; or it may be due to a "group think" phenomenon where the members of the group converge in their opinions because they simply neglect dissonant information.

Errors of judgment can thus be analyzed as a problem of divergence between the organization and the individual regarding:

(1) the interpretation of data (thus their assessments of risks and uncertainties), and

(2) preferences and risk attitudes that result from the inherent behavioral tendency of the individual and the organization's reward system.

In the analysis of errors of judgment, two categories are defined (Figure D.2): bad judgment at the individual level (either in interpretation of information or in preferences), and good individual judgment (given the constraints imposed on the employee and his own risk attitude) leading to individual decisions that go against the interest and preferences of the organization and thus appears as bad judgment at the corporate level. The first category (bad judgment at the individual level) is divided further among: reckless behavior, wrong learning mechanisms, refusal to believe or to use available information about uncertain quantities, and misunderstanding of goals or violation of the organization's rules.

Errors of judgment (as well as gross errors) occur at different rates in the different subsystems --according, for instance to the uncertainties involved. The probabilities of detection of these errors vary with their nature and their severity. In addition, their effect on the probability of system failure also depends on their nature and their severity.

The relevant parameters for the analysis of the platform structure system failures are thus the following:

a) The global base rate of errors.

b) The probability that an error occurs in a specific subsystem conditional on its occurrence in the system as a whole. It is assumed here that, as a first approximation, the probability that errors occur in more than one subsystem is negligible compared to the probability of occurrence in only one of them.

c) The probability of different types of errors in each of the subsystems conditional on error occurrence in that subsystem. The analysis of error types is reduced here for simplicity to gross errors (GE) and errors of judgment (EJ). This distinction is important because reduction of their probabilities of occurrence relies on different types of management improvement measures.

d) The probability of different levels of error severity. For simplicity, only two levels of severity are considered here: high severity (HS) less frequent but more easily detectable, and low severity (LS) more frequent but more likely to pass undetected through the filters of the review process. When undetected or uncorrected, high-severity errors are more likely to lead to system failure than low-severity errors.

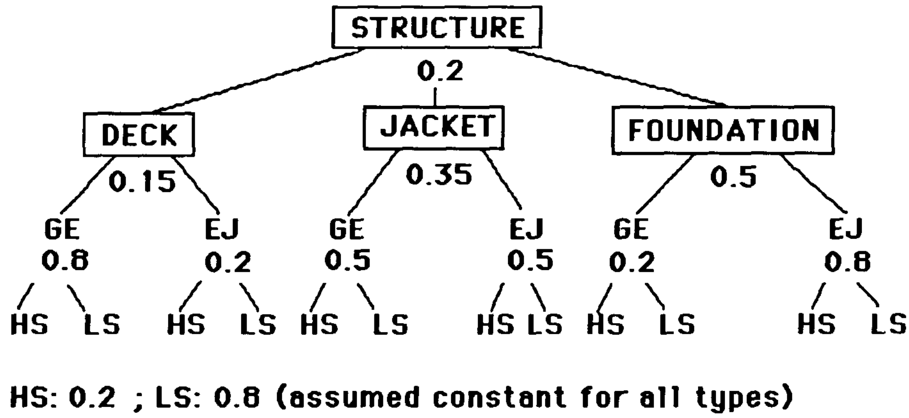

Figure D.3 - Error analysis for design of a jacket-type offshore platform

Figure D.3 shows a set of illustrative values for a jacket-type offshore platform (Figure D.1). The overall base rate of design errors for all jacket-type structures is estimated at 20%. These errors are further allocated among the different subsystems. Errors across subsystems may well occur. This can be the case, for example, if the design relies on a bad theory of the waves and their annual probabilities, therefore affecting the design of all subsystems.

The simple allocation used here relies on a "dominant error" concept, i.e., that which is most likely to cause an initiating failure. Errors associated to the interface between the deck and the jacket have been attributed here to the jacket. For example, the deck may be too low causing the jacket's joints to be subjected to severe wave loads.

Note that the conditional probability of gross error for the foundation is 0.2, that the probability of error of judgment is 0.8 and that these probabilities are reversed for the deck. This assessment is based on the knowledge that there are more uncertainties and more subjectivity in the design of the foundation than in the design of the deck. The design of foundations that are located in variable and inhomogeneous soils is more likely to rely on "judgement" than the design of the deck.

As an illustration, the conditional probability of high-severity vs low-severity error was chosen to be 0.2 (vs 0.8) across the different types of errors and the different subsystems.

Detection of Design Errors by Checking

The design review process developed in thies example is sequential. The first review is performed by the lead engineer, typically competent and knowledgeable, but not necessarily someone who has had a long experience in the field. He is thus more likely to detect gross errors than errors of judgment. Also, high-severity errors are more visible than low-severity ones and are therefore more likely to be detected at all stages of the review. If he detects an error (Signal 1), it is assumed that the correction process will take place with a rate of success that depends on the nature of the error: a gross error is more likely to be corrected than an error of judgment that the author of the error may seek to defend even if it is detected.

The second review level is performed by the engineering manager, generally a person of experience who may not check the detail of all computations but will detect errors of judgment more easily than the lead engineer (Signal 2). Finally, the constructor may detect an error when actually doing the work on the field (Signal 3). At this late stage and given the constructor's experience, it will be easier to detect gross errors than errors of judgment about which he may have little to say.

It is assumed that the review process is the same for the different subsystems (foundation, deck, and jacket) although the details of the procedure obviously vary.

Figure D.4 shows a schematic representation of the probabilistic analysis of the review process with illustrative numbers corresponding to the case of gross errors of high severity in the design of the foundation. The foundation can start with a gross error (GE), an error of judgment (EJ), or no initial error (NIE). Errors of high or low severity can be detected or missed by the successive reviewers. It is assumed that following corrective action (CA), the system is returned to the capacity of the structure had no error occurred in the first place.

Table D.1 presents illustrative numbers for the probability of detection and correction of design errors assuming for simplicity that the review process and the probabilities of signal observation are the same for the different subsystems.

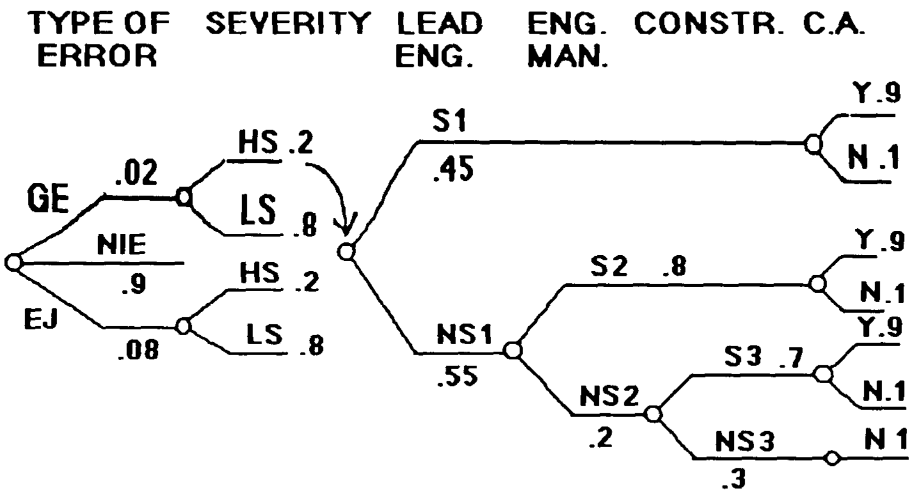

Figure D.4 - Probability of detection of errors in the design of foundations (illustrative valuesfor Gross Errors, GE, f High Severity, HS)

Table D.1 - Probability of detection and correction of design errors by the different levels of review

Type of Error	Lead Engineer	Engineering Manager	Constructor	Corrective Action
GE, HS	0.45	0.80	0.70	0.90
GE, LS	0.20	0.65	0.40	0.60
EJ, HS	0.20	0.50	0.10	0.60
EJ, LS	0.05	0.30	0.01	0.20

*Probability that successful correction occurs given that an error has been detected at one of the review levels.
GE: Gross Error; EJ: Error of Judgement;
HS: High Severity; LS Low Severity

In this model, the probability that corrective action actually occurs conditional on error detection does not depend on who discovered the error but on its nature and degree of severity. The probability of successful corrective action conditional on an error of judgment of low severity has been assumed to be low because it is more difficult in this case to argue in favor of slowing down for correction. If a corrective action is successful, it is assumed that the system is back to a no-error state. If it is not successful, it is assumed that the

status quo prevails and that the system is neither stronger nor weaker than if the error had not been observed at all.

At the beginning of the review process, the system can be in three different states: no initial error (NIE), low-severity initial error (LIE), or high-severity initial error (HIE). At the end of the process, there may be no final design error (NDE) (either because there was no error in the first place, or because initial errors were detected and corrected), undetected design error of high severity (HDE), or undetected design error of low severity (LDE).

No distinction is made here among errors of the same severity regarding their nature (GE or EJ) because it is assumed that this characteristic does not influence the probability of failure. The different levels of errors in the final states are the result of the logical analysis of the sequence of errors occurrence, detection, and correction.

The occurrences of NDE, LDE, and HDE can be written:

NDE = NIE + EJ x observation x correction + GE x observation x correction (D.3)

LDE = GE x LIE x (no observation + observation x no correction) + EJ x LIE x (no observation + observation x no correction) (D.4)

HDE = GE x HIE x (no observation + observation x no correction) + EJ x HIE x (no observation + observation x no correction) (D.5)

Observation = S1 + (NS1 x S2) + (NS1 x NS2 x S3) (D.6)

Given the data described above, this implies for the foundation the following distribution for the final error states:

p(NDE) = 0.9220
p(LDE) = 0.0676
p(HDE) = 0.0104

Note that, in relative terms, the review process increases little the probability of no design error (from 0.9 to 0.922) but decreases considerably the relative rate of high- severity errors (from 0.02 to 0.01).

Probability of Structural Failure Due to Design Errors

The effect of the error detection and correction process is a variation in the capacity of the system to withstand loads such as waves.

Failure of the Foundation

Focusing for the moment on the possibility of failure of the foundation (O), assume the following annual failure probabilities for each of the final system states:

$$p(O \mid NDE) = 3.5 \times 10^{-5}$$
$$p(O \mid LDE) = 3.5 \times 10^{-4}$$
$$p(O \mid HDE) = 3.5 \times 10^{-2}$$

Failure of the foundation given no final design error corresponds either to errors in other project phases (construction or operations) or to inherent randomness in the occurrence of the loads. The former is the most frequent case as shown below. The latter represents the rare instances where the external loads exceed the design level (and implicit safety margins) that had been chosen in the first place.

Generally defining as S the level of error severity, $f_S(s)$ its probability density function, and $p(O \mid s)$ the conditional probability of failure of the foundation given an error level s, the probability of foundation failure can be written:

$$p(O) = \int f_S(s) \times p(O \mid s)\, ds \qquad (D.7)$$

In the simple case of three error levels considered here, the probability of foundation failure is:

$$p(O) = p(O, NDE) + p(O, LDE) + p(O, HDE) \qquad (D.8)$$

$$p(O) = p(NDE) \times p(O \mid NDE) + p(LDE) \times p(O \mid LDE) + p(HDE) \times p(O \mid HDE) \qquad (D.9)$$

Given the probabilities of final error states computed above (e.g., undetected low-severity design error) and the failure probabilities in each case, the annual probability of failure for the foundation is thus:

$$p(O) = p(O \mid NDE) \times p(NDE) + p(O \mid LDE) \times p(LDE) + p(O \mid HDE) \times p(HDE) \qquad (D.10)$$

Thus,

$$p(O)= 0.9220 \times 3.5 \times 10^{-5} + 0.0676 \times 3.5 \times 10^{-4} + 0.0104 \times 3.5 \times 10^{-2}$$

and, $p(O)= 4.2 \times 10^{-4}$.

Of this total foundation failure probability per year, *86% are attributable to undetected design errors of high severity, 6% to undetected design errors of low severity, and 8% to no design error situations.* Although high-severity errors are rare, the resulting probability of foundation failure is large, hence their high contribution to the overall failure probability for the foundation.

As it will become clear in the second phase of the computations (cumulation of errors), this is due to the fact that design errors were found to be a major source of foundation failures, whereas construction errors are less critical and operation errors are still less likely to affect the foundation.

Failure of the Jacket

The only change in the data with respect to the previous computations are assumed to be the overall probability of occurrence and the rates of gross errors (50%) and errors of judgment (50%) given design error for the jacket. Conditional observation of signals and effectiveness of corrective actions are assumed to be the same.

On the basis of these data, the probabilities of the different states of the jacket at the end of the review process are the following:

$p(NDE)= 0.9547$ (from 0.93 initial no error rate)
$p(LDE) = 0.0401$ (from 0.056)
$p(HDE) = 0.0052$ (from 0.014)

Again, in the case of the jacket, the design review process increases little the probability of no design error and mainly reduces the probability of high-severity errors. The probability of failure of the jacket conditional on different structural states (due to the occurrence of design errors) can be the result of a detailed PRA taking into account the specific types of errors and their effect on the structure, as well as the loads' distribution. Estimates of these probabilities are the following:

$p(A \mid NDE) = 3 \times 10^{-4}$
$p(A \mid LDE) = 5 \times 10^{-3}$
$p(A \mid HDE) = 2 \times 10^{-2}$

The total annual probability of failure of the jacket is then:

$$p(A) = p(A \mid NDE) \times p(NDE) + p(A \mid LDE) \times p(LDE) + p(A \mid HDE) \times p(HDE) \quad (D.11)$$

$$p(A)= (3\times10^{-4} \times 0.9547) + (5 \times 10^{-3} \times 4.106 \times 10^{-2}) + (2 \times 10^{-2} \times 5.22 \times 10^{-3})$$

$p(A) = 6.06 \times 10^{-4}$

Accounting for all possible states of the structure resulting from the occurrence of errors, the probability of failure of the jacket itself is about 6×10^{-4}, of which *47% can be attributable to situations in which there was no error in the final design, 33% to undetected low-severity design errors, and 20% to undetected high-severity design errors.* The contribution of the no-design-error scenario to the overall probability of failure is much larger than for the foundation because, as it is shown later in this paper, the jacket is also vulnerable to construction errors and, to a smaller extent, to operations errors which contribute a large part of the overall failure probability without necessarily involving design errors.

Failure of the Deck

In the case of failure of the deck component, the same method is applied. The main changes are the base rate (3%) and the rate of gross errors (80%) as opposed to errors of judgment (20%). Given the high rate of more easily detectable gross errors in the design, the probability of undetected errors is smaller than for the rest of the platform.

Given that only 3% of the platforms are assumed to experience any error in the initial deck design, the probability distribution obtained through the model for the different states of the deck after review of the design is the following:

$p(NDE) = 0.9845$ (from 0.97 before the review process)
$p(LDE) = 0.0141$ (from 0.024)
$p(HDE) = 0.0014$ (from 0.006)

The probability of failure of the deck depends in large part on the occurrence of external events such as fires and blowouts that are not as dependent of the deck design (in occurrence and consequences) as the effects of external loads on other subsystems. It is thus less sensitive to errors in the structural design than the jacket or the foundation that are subjected regularly to wave loads. The annual probability of failure of the deck conditional on the different states corresponding to the levels of severity of design errors are estimated to be the following:

$p(E \mid NDE) = 10^{-3}$
$p(E \mid LDE) = 3 \times 10^{-3}$
$p(E \mid HDE) = 10^{-2}$

The overall annual probability of failure of the deck is thus:

$$p(E) = p(E \mid NDE) \times p(NDE) + p(E \mid LDE) \times p(LDE) + p(E \mid HDE) \times p(HDE) \quad \text{(D.12)}$$

$$= (10^{-3} \times 0.9845) + (3 \times 10^{-3} \times 1.41\times10^{-2}) + (10\text{-}2 \times 1.4\times10^{-3})$$
$$= 9.8 \times 10^{-4} + 5.16 \times 10^{-5} + 2.24 \times 10^{-5}$$
$$= 1.05 \times 10^{-3}$$

The probability of failure of the deck, which is about 10^{-3}, is thus the dominant element of the overall failure probability for the platform. The percentage of failures that occur without design errors (but may be caused by other types of errors and external events due to production activity on the deck) represent 93% of the overall failure probability; low-severity and high-severity errors in the final design account only respectively for 5% and 2% of the probability of failure of the deck.

The results are presented in Table D.2. They show the contribution of each of the subsystems to the overall failure probability, and also the contribution of the types of error given their nature and their severity. Further analysis of the different types of organizational errors can then be used to compute the reduction in the global failure probability that can be expected from the reduction of the rate of errors of different types.

Table D.2 - Annual probability of failure of an offshore platform for contribution of gross errors and errors of judgement in the design phase

Subsystem / Design Err.	Foundations	Jacket	Deck	Whole structure	
				Failure Prob.	Percentage
High Sev.	**3.6 x 10-4**	**10-4**	**2.2 x 10-5**	**4.8 x 10-4**	**25%**
Gross Er.	7.2 x 10-5	5 x 10-5	1.8 x 10-5	1.4 x 10-4	7%
Er. of Judg.	2.9 x 10-4	5 x 10-5	4.4 x 10-6	3.4 x 10-4	18%
Low Sev.	**2.4 x 10-5**	**2 x 10-4**	**5.2 x 10-5**	**2.9 x 10-4**	**15%**
Gross Er.	4.8 x 10-6	10-4	4.2 x 10-5	1.5 x 10-4	8%
Er. of Judg.	1.9 x 10-5	10-4	10-5	1.3 x 10-4	7%
No Error	**3.2 x 10-5**	**2.9 x 10-4**	**9.8 x 10-4**	**1.3 x 10-3**	**60%**
Total	**4.1 x 10-4**	**6.1 x 10-4**	**10-3**	**2.2 x 10-3**	**GE: 15%** **EJ: 25%** **NE: 60%**

Errors in Design, Construction, and Operations

Historical analysis of failures shows that failures often occur when several errors contribute to weakening a platform. In cases where no design error has occurred, errors in construction or operations phases can cause a platform failure. The following analysis allows extension of the previous computations to include not only design errors but also construction and operations errors.

Note that the probabilities computed so far *include implicitly the possibility of additional errors in the estimate of p(F) conditional on the different levels of design error.* In this section, the cumulation is considered explicitly. The annual probabilities of construction and operation errors are assumed to be the results of a process analysis similar to the one developed in the previous sections for design errors. The results are the probabilities of errors of different severity levels in the different phases. It is assumed here that design errors, construction errors, and operation errors are independent among themselves and independent across subsystems.

For illustrative purposes, the distributions of undetected/uncorrected construction errors for each of the subsystems were assumed to be similar to those of design errors.

Construction errors in the foundation:

- No Error (NCE): $p_O(NCE) = 0.9220$
- Low severity (LCE): $p_O(LCE) = 0.0676$
- High severity (HCE): $p_O(HCE) = 0.0104$

Construction errors in the jacket:

- $p_A(NCE) = 0.9547$
- $p_A(LCE) = 0.0401$
- $p_A(HCE) = 0.0052$

Construction errors in the deck:

- $p_E(NCE) = 0.9845$
- $p_E(LCE) = 0.0141$
- $p_E(HCE) = 0.0014$

The annual distribution for operations errors is assumed to be the same for the three subsystems and was estimated as follows:

- No error (NOE): $p(NOE) = 0.85$
- Low severity (LOE): $p(LOE) = 0.10$
- High Severity (HOE): $p(HOE) = 0.05$

Effects of Error Culmination

The probabilities of failure of the different subsystems (foundation, jacket, and deck) are entered in this model as conditional probabilities given the possible combinations of errors of different types (ex: construction) and different severity levels (ex: high severity). *These probabilities of failure are treated here as data based on expert opinions.*

These failure probabilities for each scenario of error combination can also be obtained as the results of detailed PRAs, in which the nature of the different types of errors are specified, and the couplings of their effects are explicitly considered in the computation of the failure probability.

The conditional probabilities of failure for each subsystem X given a particular level of design error (DE) is the sum for all severity levels of construction errors (CE) and operations errors (OE) of the joint probability of failure and errors divided by the probability of the design error after the review and correction process has taken place. Because the occurrence of errors of different types are assumed to be independent events, the joint probability of errors is the product of their marginal probabilities.

$$p(X \mid DE) = p(X, DE) / p(DE) \quad \text{(D.13)}$$

$$= \Big[\sum_{CE} \sum_{OE} p(X, DE, CE, OE)\Big] / p(DE) \quad \text{(D.14)}$$

$$= \Big[\sum_{CE} \sum_{OE} p(X \mid DE, CE, OE)\, p(DE, CE, OE)\Big] / p(DE) \quad \text{(D.15)}$$

$$= \sum_{CE} \sum_{OE} [p(X \mid DE, CE, OE)\, p(CE)\, p(OE)] \quad \text{(D.16)}$$

The assembly model (from initial errors to review, correction, and final error levels in design, construction, and operations) is an ETA that is described and processed here as an IDA. One IDA was developed for each of the subsystems. Figure D.5 shows a global IDA for the foundation.

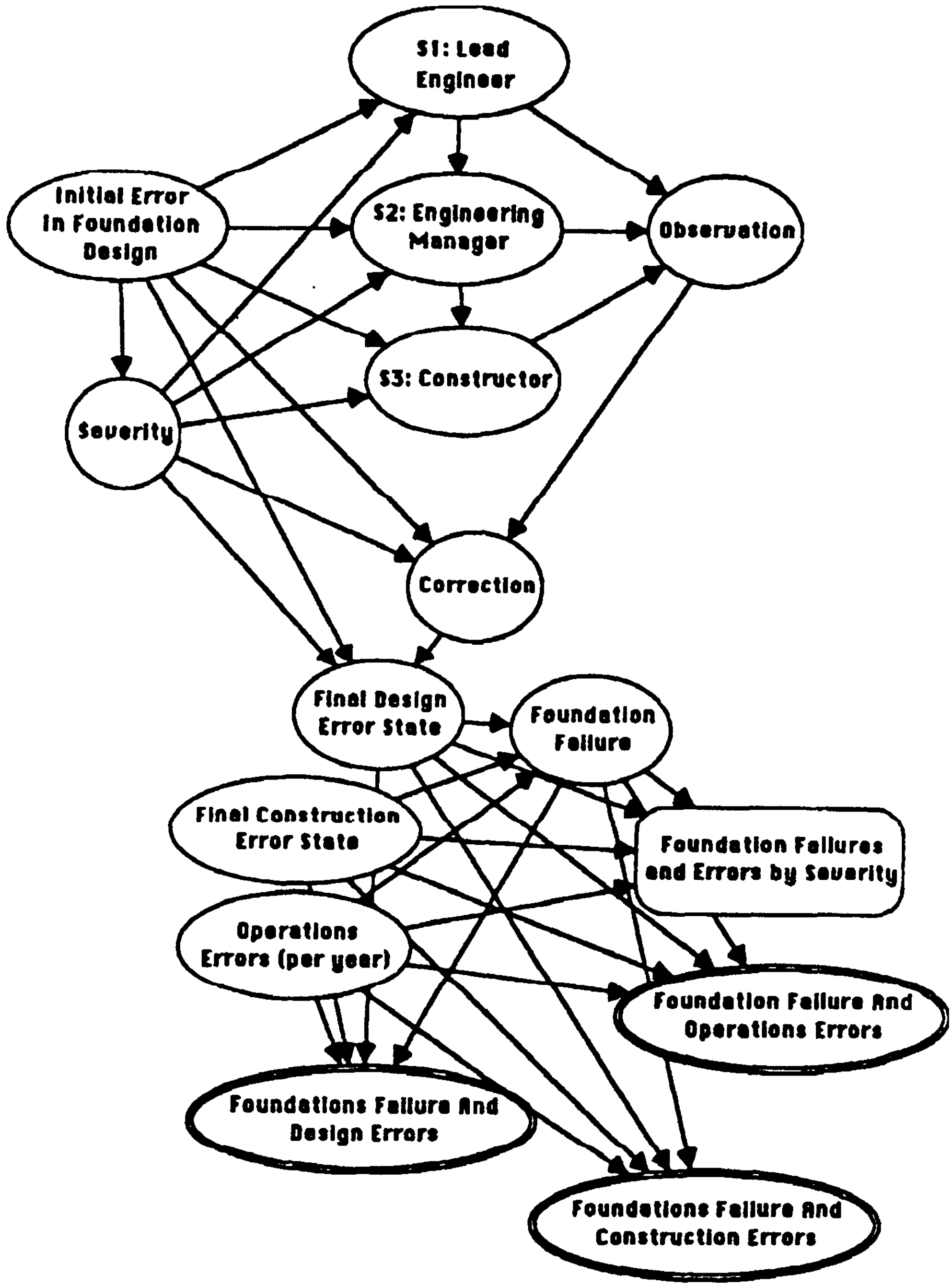

Figure D.5 - IDA for the design, construction, and operation life-cycle phses of the foundation

The severity that characterizes a cumulation of errors is taken as the highest severity level in the error combination: for instance, a situation such as {no design error, high-severity construction error, no operation error} is classified in the end as a high-severity error situation. The results of the analysis include first a probability distribution for the failure/no failure situations allocated among the different levels of dominant errors (square box)

and second, the joint distribution of failure states and error severities for each phase of the platform lifetime (design, construction, and operation) shown on the influence diagram in the oval double boxes.

Table D.3 summarizes the final results allocated among subsystems (e.g. jacket) and severity of the dominant error in each combination (e.g., high-severity construction error in the scenario: LDE, HCE, NOE). Note that the percentages shown in Table D.3 reflect the contribution of the dominant error alone. Yet, low-severity errors can act as "catalysts" in such scenarios because they worsen the effect of a concurrent high-severity error. Their contribution to the overall failure probability (17%) is thus underestimated by this method.

Table D.3 - Probability of failure of example platform with cumulation of errors in design, construction, and operations

Subsystem	O Fdn.	A Jacket	E Deck	Whole Structure	Percent of Total
HS	3.9×10^{-4}	4.1×10^{-4}	8.0×10^{-4}	1.6×10^{-3}	79 %
LS	1.7×10^{-5}	1.7×10^{-4}	1.7×10^{-4}	3.5×10^{-4}	17 %
NE	7.2×10^{-6}	3.1×10^{-5}	4.1×10^{-5}	7.9×10^{-5}	4 %
Total	4.1×10^{-4}	6.1×10^{-4}	1.0×10^{-3}	2.0×10^{-3}	100 %

HS: High Severity Errors; LS: Low Severity Errors; NE: No Errors

The annual probability of failure can no longer be attributed in a simple manner among design, construction, or operations since all combinations are assumed possible and each type contributes to the overall failure probability. In particular, errors of different types but of the same severity may be dominant in the same combination (e.g., high severity construction error and high severity operations error). Note that the probability of failure and no error has considerably decreased compared to the previous analysis of failures due to design errors alone because it means, in this phase of the computations, that no error occurred at all neither in design, nor construction, nor operations (as opposed to no error in design alone).

The results also include the joint probability of failure for each of the subsystems and a given level of error of each type (design, construction, operations) as well as the corresponding conditional probabilities of failure given a particular level and type of error. For each type of error, these results show the corresponding allocation of the subsystems' annual failure probability

among the different levels of error severity for each error type. The spread of the conditional distribution characterizes the sensitivity of the system to errors of the corresponding type.

For the foundation, design errors are the most critical, and high-severity design errors clearly dominate the joint distribution. The conditional distribution of failure given error severity shows a wide spread (three orders of magnitude) and a large increase (two orders of magnitude) between effects of low- and high-severity errors. Construction errors are less critical, with a joint distribution (failure and errors' severity) dominated by "failure and low-severity errors".

Note that this is one of the cases where low-severity errors become dominant because they are more frequent than the high- severity ones but decrease the system's capacity sufficiently to make operations errors more dangerous and external events (e.g., blowouts) more damaging. Finally, in general, operations errors are not very critical: failure and no operations error dominates the joint distribution (failure and severity of errors). Accordingly, the conditional probability of failure given operations error levels is tight and ranges over less than one order of magnitude.

For the jacket, design and construction errors are equally critical with conditional distributions spread over two orders of magnitude between failure given no error and failure given high-severity errors. Operations errors are less critical although they affect the jacket a little more than the foundation (over one order of magnitude in the range of conditional failure probability).

For the deck, operations errors are the most critical, with failure given no error on the order of 10^{-5} and failure given high-severity errors on the order of 10^{-2}. In the joint distribution of failure and errors of different levels of severity, the dominant term is due to high-severity errors ($8x10^{-4}$) with a non negligible contribution of failures and low- severity errors. Design and construction are less critical but still affect the deck to the extent that they amplify the effects of operations errors (e.g., poor design against fire) or that they make the deck more susceptible to high levels of wave loads.

Note that the results are annual probabilities of failure. For operations errors, it is assumed that the rates of errors and their effects on the platform remain invariant. In design and construction, errors occur once and for all. It is assumed here that the annual failure probability does not vary given the occurrence of errors of different severity levels. In fact, this may not be the case: if failure has not occurred at any given year, it may be that the probability that it occurs the following year decreases.

Results of Improvement in Design Review

Improvement in the design review process can be achieved by the intervention of a certified verifying authority. A high-quality verification process could modify the probabilities of undetected gross errors and judgmental errors, of low and high severity, in the foundations, the jacket, and the deck.

Table D.4 summarizes the variations of design error probabilities with improvements of the review process. The following estimates reflect the possible reductions in probabilities of failure of the platform components that can be achieved by an improvement of the review process:

$$p'(O) = 0.96 \times 3.5 \times 10^{-5} + 0.035 \times 3.5 \times 10^{-4} + 0.005 \times 3.5 \times 10^{-2}$$
$$= 2.21 \times 10^{-4} \quad (\text{from } p(O) = 4.2 \times 10^{-4})$$

$$p'(A) = 0.97 \times 3 \times 10^{-4} + 0.028 \times 5 \times 10^{-3} + 0.002 \times 2 \times 10^{-2}$$
$$= 4.71 \times 10^{-4} \quad (\text{from } p(A) = 6.06 \times 10^{-4})$$

$$p'(E) = 0.99 \times 10^{-3} + 0.009 \times 3 \times 10^{-3} + 0.001 \times 10^{-2}$$
$$= 1.027 \times 10^{-3} \quad (\text{from } p(E) = 1.05 \times 10^{-3})$$

$$p'(F) = 2.21 \times 10^{-4} + 4.71 \times 10^{-4} + 1.027 \times 10^{-3}$$
$$= 1.72 \times 10^{-3} \quad (\text{from } p(F) = 2.2 \times 10^{-3})$$

Note that this improvement of the review process reduces mostly the probability of failure of the foundation (approximately by a factor of two), to some extent the probability of failure of the jacket (by about twenty percent), and reduces little the probability of failure of the deck that is more susceptible to operations errors than design errors. Because the major contributor to the platform failure is the deck, the reduction of the overall failure probability is only 22%. If in addition to correcting errors in design, the design of the deck is also modified to decrease the consequences of operations errors (for example, preventing fire propagation), major gains can be achieved by design changes alone.

Table D.4 - Estimated variations of design error probabilities with improvements of the review process

Subsystem / Errors	Foundation		Jacket		Deck	
	From	To	From	To	From	To
No Error	0.922	0.96	0.955	0.97	0.9845	0.99
Low Severity	0.0672	0.035	0.041	0.028	0.0141	0.009
High Severity	0.0104	0.005	0.0052	0.002	0.0014	0.001

Project Technical Committee Members

The following persons were members of the committee that represented the Ship Structure Committee to the Contractor as resident subject matter experts. As such they performed technical review of the initial proposals to select the contractor, advised the contractor in cognizant matters pertaining to the contract of which the agencies were aware, and performed technical review of the work in progress and edited the final report.

Dr. Jack Spencer	American Bureau of Shipping
Dr. William Moore	American Bureau of Shipping
Mr. John Conlon	American Bureau of Shipping
Mr. Alexander Landsburg	Maritime Administration
Mr. Fred Seibold	Maritime Administration
LT Robert Holzman	U.S. Coast Guard
Mr. Mark Mandler	U.S. Coast Guard
Mr. Zbigniew Karaszewski	U.S. Coast Guard
Mr. Thomas Hu	Defence Research Establishment Atlantic
Mr. Palmer Luetjen	Naval Sea Systems Command
Mr. Subodh Prasad	Naval Sea Systems Command
Dr. Marc Wilson	Dowling College
Prof. Paul S. Fischbeck	Carnegie Mellon University
Mr. William Siekierka	Naval Sea Systems Command, Contracting Officer's Technical Representative
Dr. Robert Sielski Mr. Alex Stavovy	National Academy of Science, Marine Board Liaison
CDR Steve Sharpe	U.S. Coast Guard, Executive Director Ship Structure Committee

SHIP STRUCTURE COMMITTEE PUBLICATIONS

SSC-356 Fatigue Performance Under Multiaxial Load by Karl A. Stambaugh, Paul R. Van Mater, Jr., and William H. Munse 1990

SSC-357 Carbon Equivalence and Weldability of Microalloyed Steels by C. D. Lundin, T. P. S. Gill, C. Y. P. Qiao, Y. Wang, and K. K. Kang 1990

SSC-358 Structural Behavior After Fatigue by Brian N. Leis 1987

SSC-359 Hydrodynamic Hull Damping (Phase I) by V. Ankudinov 1987

SSC-360 Use of Fiber Reinforced Plastic in Marine Structures by Eric Greene 1990

SSC-361 Hull Strapping of Ships by Nedret S. Basar and Roderick B. Hulla 1990

SSC-362 Shipboard Wave Height Sensor by R. Atwater 1990

SSC-363 Uncertainties in Stress Analysis on Marine Structures by E. Nikolaidis and P. Kaplan 1991

SSC-364 Inelastic Deformation of Plate Panels by Eric Jennings, Kim Grubbs, Charles Zanis, and Louis Raymond 1991

SSC-365 Marine Structural Integrity Programs (MSIP) by Robert G. Bea 1992

SSC-366 Threshold Corrosion Fatigue of Welded Shipbuilding Steels by G. H. Reynolds and J. A. Todd 1992

SSC-367 Fatigue Technology Assessment and Strategies for Fatigue Avoidance in Marine Structures by C. C. Capanoglu 1993

SSC-368 Probability Based Ship Design Procedures: A Demonstration by A. Mansour, M. Lin, L. Hovem, A. Thayamballi 1993

SSC-369 Reduction of S-N Curves for Ship Structural Details by K. Stambaugh, D. Lesson, F. Lawrence, C-Y. Hou, and G. Banas 1993

SSC-370 Underwater Repair Procedures for Ship Hulls (Fatigue and Ductility of Underwater Wet Welds) by K. Grubbs and C. Zanis 1993

SSC-371 Establishment of a Uniform Format for Data Reporting of Structural Material Properties for Reliability Analysis by N. Pussegoda, L. Malik, and A. Dinovitzer 1993

SSC-372 Maintenance of Marine Structures: A State of the Art Summary by S. Hutchinson and R. Bea 1993

SSC-373 Loads and Load Combinations by A. Mansour and A. Thayamballi 1994

SSC-374 Effect of High Strength Steels on Strength Consdierations of Design and Construction Details of Ships by R. Heyburn and D. Riker 1994

None Ship Structure Committee Publications - A Special Bibliography